SYSTEM CONCEPT DESCRIPTION
PHASE A
FOR INFRARED ASTROPHYSICS
STRATOSPHERIC OBSERVATORY
FOR INFRARED ASTROPHYSICS (SOFIA)
FOREWORD

Infrared astronomers have made significant discoveries using the NASA/Ames Research Center C-141 Kuiper Airborne Observatory (KAO) with its 0.91-meter telescope. The need for a 3-meter class airborne observatory has been established to improve astronomy data gathering capability. The new system envisioned by NASA and the international community of astronomers will be known as the Stratospheric Observatory for Infrared Astronomy (SOFIA). The platform of choice for SOFIA is a modified Boeing 747SP.

SOFIA is viewed as a logical progression from the KAO. Potentially, a 3-meter telescope operating at the altitude achievable by the 747SP aircraft can be 11 times more sensitive than the KAO, can have 3.3 times better angular resolution, and will allow observations of compact sources in a volume of space up to 36 times that of the KAO. The KAO has enabled detection of about 15 percent of the far infrared IRAS survey point-sources; SOFIA should be able to detect them all.

This document presents the results of in-house ARC and contracted concept definition studies for SOFIA. Using the ARC-based Kuiper Airborne Observatory as a basis for both SOFIA design and operations concepts, the SOFIA system concept has been developed with a view toward demonstrating mission and technical feasibility, and preparing preliminary cost estimates. The reference concept developed is not intended to represent final design, and should be treated accordingly.

The most important products of this study, other than demonstration of system feasibility, are the understanding of system trade-offs and the development of confidence in the technology base that exists to move forward with a program leading to implementation of the Stratospheric Observatory for Infrared Astronomy (SOFIA).
SOFIA REPORT OUTLINE

This report is organized to lead readers through the development of a design concept for the SOFIA Observatory, recognizing that these steps are not consecutive, but parallel and interactive as system issues cross the identified boundaries. The contents of each major section are identified on the initial page for that section. The Introduction/Overview section provides an executive summary of the study background, requirements, and objectives, and a top-level system concept description. Section 2 describes the science rationale and objectives, science comparison with other facilities, and science instrument overview. Section 3 addresses the top-level telescope system description, including constraints, budgets, and interfaces. Section 4 details the telescope subsystems’ design concepts and analyses. Section 5 presents a description of the aircraft system, including key features, performance, and equipment accommodations. Section 6 outlines the proposed integration and test program, from subsystem to Observatory level. Section 7 describes the proposed Observatory ground support system, including facilities and equipment needed to support science investigators, the telescope and the aircraft. Section 8 addresses concepts for the SOFIA mission and science operations, both ground and flight. The report is generally in the format of annotated charts and figures, with text on the left and relevant tabular or graphic material on the right of each pair of facing pages.
# TABLE OF CONTENTS

1.0 INTRODUCTION/OVERVIEW  
2.0 SCIENCE  
3.0 TELESCOPE SYSTEM DESCRIPTION  
4.0 TELESCOPE SUBSYSTEMS DESCRIPTION  
5.0 AIRCRAFT SYSTEM DESCRIPTION  
6.0 INTEGRATION AND TEST  
7.0 GROUND SUPPORT SYSTEM  
8.0 OPERATIONS SYSTEM
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INTRODUCTION/OVERVIEW

1.1 Background

The history of the concept for a large airborne IR telescope began circa 1965 when Dr. M. Bader, of the ARC Physics Branch, inaugurated NASA’s assignment of an aircraft for airborne scientific research with the use of NASA’s CV-990 (#711) for near-infrared observations of celestial objects. In 1969, the first flight of a 30 cm open-port telescope in ARC’s Lear Jet took place; also at that time, planning started for installation of a 91 cm telescope in the CV-990, later changed to a C-141 aircraft. With the advent of the Boeing 747 in 1969, first astronomy community interest in that platform was voiced, and C. Gillespie of ARC initiated contact with Boeing while witnessing the first Boeing 747 flight at Everett, Washington. By 1972 the Kuiper Airborne Observatory (KAO) development was well along, and that year the Greenstein report was published calling for construction of a "Large Stratospheric Telescope" to be "...implemented toward the end of the decade...". In 1974, the first research flight of the KAO took place, studies began on a larger telescope in a larger aircraft, and the first NASA discussions were held with Boeing representatives who pointed out the advantages of the 747SP (Special Performance) aircraft for such a system. From 1975 to 1979 planning for a "Large Airborne Telescope" (LAT) continued at a low level while NASA/Headquarters and ARC were occupied with other projects. As KAO operations became very productive, the astronomy community recognized more and more the potential gains to be achieved with a larger telescope. By June 1980, the KAO staff had developed a conceptual summary for the LAT, and a paper, "Three Meter Telescope on a 747SP Platform" was presented at the IAU Symposium #86 in Hawaii, by R. Cameron, Chief of ARC’s Medium Altitude Missions Branch. During 1980-1983, the IRAS and SERTF projects continued to occupy attention and resources of Headquarters and ARC; with the successful 1983 IRAS mission, the need was seen for follow-up and exploitation of its IR survey observations. By 1984 momentum had rekindled for the LAT, with renewed ARC advocacy and increased interest of Headquarters program offices. An "ad hoc" advocacy group of infrared astronomers was formed, and Roger Hildebrand (U. Chicago) delivered a paper on "The Large Airborne Telescope" at the KAO’s 10th anniversary symposium. Also in 1984, a report "SOFIA/Preliminary Feasibility Study" was issued for the renamed observatory concept at Headquarters request, by the KAO staff and the Scientists Support Group (now Science Consulting Group). In 1985, Drs. Keller and Pellerin at Headquarters programmed FY 86 funds for a Phase I study with Boeing Military Airplane Company on Boeing 747SP modifications for SOFIA. The study started in 1986 under the newly-formed ARC SOFIA Study Office, which also initiated the in-house Telescope System Phase A study.
SOFIA HISTORY

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1.2 General Requirements

Aircraft Performance Requirements

The performance requirements for the SOFIA aircraft are based on NASA's experience with flying science and deployment missions on the Kuiper Airborne Observatory (KAO). For the deployment mission, this includes the capability to transport: an investigator and mission team of about 40 personnel (including flight crew(s)); cargo (including SOFIA-peculiar ground support equipment) of up to 46,520 lbs; and the SOFIA telescope system, a distance of 6,000 nautical miles with weather reserves. This assumes standard atmospheric conditions, no wind, and no drag increase due to the aircraft modification; the latter assumption is optimistic as there is liable to be a small drag penalty due to the aircraft contour changes around the (closed) cavity door. This distance is sufficient for a non-stop deployment to Australia, a preferred operating base for viewing southern declination targets.

For the science missions, a total flight duration of seven to eight hours, including 6.5 hours with telescope cavity door open at or above the preferred altitude of 41,000 feet, is a reasonable upper limit considering human factors and crew duty time limitations. The 41,000 foot level is assigned due to the IR- obscuring atmospheric telluric water vapor overburden, which is at only a 1% of its ground-level value at that altitude; the long endurance is necessary for an efficient science program (relative to operational cost). The time to climb requirement of 1/2 hour includes door opening and boundary layer control (BLC) fence deployment at altitude; an additional 1/2 - 1 hour is assumed for descent and landing, giving a total flight duration of 8 hours at most. The payload assumed for this mission is 71,805 lbs, including the cavity modification, telescope system, mission/science systems, ballast, and crew, science, and mission personnel. To achieve this endurance, the drag increase associated with the deployed BLC fence and open cavity will have to be held to approximately a 20 square foot "flat plate equivalent," which appears achievable. In addition, engines with "enhanced performance" modifications may be required to achieve the operating time at altitude requirement.

The platform (aircraft) attitude accuracy and stability requirements are important considerations in design of the telescope pointing control system and sizing the cavity to accommodate telescope motions. The requirement listed is achievable with commercial autopilots assuming the values are rms. To achieve peak-to-peak values of this magnitude would require an enhanced, but also existing autopilot.

Other aircraft requirements not shown include mission equipment and science/mission team accommodations, including cabin environmental control, safety/communications equipment, electrical power outlets, equipment and utilities mounting and routing accommodations, etc. The design and development of the cavity structural modification, including the door and BLC devices, is also the responsibility of the aircraft system provider, and is described in Section 5 of this report.
Top Level Aircraft Performance Requirements

A. Deployment Mission
- 125,000 lbs total
- 6000 NM with fuel reserves
- 135 hours

B. Science Mission
- 72,000 lbs total
- 65 hours at FL 410
- 30 min to FL 410 (41,000 ft)

C. Operational Efficiency
- Capability for Payload
- Endurance at Altitude
- Time to Climb

D. Platform Attitude Accuracy/Stability
- 40° Pitch Stability
- 6° Azimuth (yaw) Accuracy/Stability
- Roll/Pitch Stability

2 x 12 Flight Operations
2 x 12 Science Makeup Flights/year
2 x 6 Engineering Flights/year
2 x 20 Science Flights/year

SOFIA
The SOFIA Science Consulting Group has established a lower limit for the primary mirror diameter of 2.5 meters with a goal of 3.0 meters, to provide a telescope with the greatest possible sensitivity and with design concepts that fit within the cavity dimensions of a modified Boeing 747SP. Current telescope and cavity design concepts are for a 3 meter primary, which appears feasible under certain conditions. A primary mirror of about 1.0 meter diameter, with interchangeable secondary mirrors providing at least 2 f/8 ratios in the range of 1.1 to 11.5, are needed to accommodate various science instrument requirements, with interchangeable secondary mirrors ranging from 1.1 to 11.5. The telescope must provide both a Cassegrain focus and a Nasmyth focus for the specified image quality. The latter is defined for on-axis sources at 0.5 microns, the effects of seeing due to shear layer and turbulence are taken into account. Provision of the Nasmyth focus is critical for allowing instrument interchange and to adjust or repair the telescope to allow recoating with vapor-deposited aluminum at least semi-annually, based on KAO experience with contamination.

The effects of seeing temperatures and their spatial distribution requirements are needed to minimize the effects of seeing and background variation. The optical and structural thermal constant requirements established for ground cooling operations.
TOP-LEVEL TELESCOPE OPTICAL SYSTEM REQUIREMENTS

- 92% AT > 10 MICRONS
  Dichroic Reflectivity
- > 70% AT 0.5 MICRONS
  Dichroic Transmissivity

Three Reflecting
Two Flats, One Dichroic Absorbing
Tertiary Mirrors

Source
Central 2m Aperture (Point Source)

AFC: 6.8 Airmass at F/18 System
- 0.3 - 1600 MICRONS
- 1.0 PRIMARY F/D
- 2.5 m (Goal: 3.0 m)

Primary Diameter

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SOFIA
Telescope Functional Requirements

The telescope system "functional" requirements are summarized. Quiescent pointing stability (smooth flight conditions) is derived from the image quality requirements, using focal plane guidance. (Note that a boresighted fine tracker camera, mounted to the telescope metering structure, will also be available for fine tracking, but with reduced accuracy/stability over a wider field-of-view.) The cavity and door are sized for a 20-60° (above horizontal) elevation range without vignetting, and ± 2° of cross-elevation and line of sight motion range; the ±4° goal for these motions may require telescope size reduction, and is under review. The 20-60° elevation range is important to allow viewing of a wide range of celestial objects from one base of departure, with minimal flight path or time of year constraints. Automatic telescope caging shall be provided if torque or motion range near limits (e.g., in turbulence). The telescope shall be capable of slewing at 24 arcmin/sec maximum, with additional requirements to provide nodding and scanning motions. An acquisition camera shall also be provided for initial coarse pointing, with zoom-out field of at least 9x10 degrees for stars of Mv≤11, and zoom-in field of 2.5x3.5 degrees for stars of Mv≤13 (at night). It shall also provide back-up tracking capability, (or tracking for large angle offsets) with ≤15 arcsec accuracy. The secondary mirror(s) shall provide "reactionless" chopping motions as shown, plus the capability to perform adjustable and dithering focusing motions. Auxiliary secondary mirror motion controls are to be provided at the experimenter control panel. Additional requirements for science instrument accommodations, cavity provisions, mission equipment/cargo accommodations, safety provisions, ground support, etc., are provided in project document PD-2000, "SOFIA and Related Requirements", which also gives greater details of the above summarized system requirements.
SENSITIVITY: TRACK ON STAB OF M=2.13
RESOLUTION & 0.15 ARCSCE
ACCURACY & 1 ARCSCE

TRACKING
FOCAL PLANE
OFFSET POINTING

MAPPING PATTERNS: CIRCULAR, SPIRAL
AMPLITUDE
NODE/SETTEL & 2 SEC. FOR 5 ARCMIN
NODE AMPLITUDE & 20 ARCMIN
2.4 DEGREES/SEC MAX STOW RATE
AUTOMATIC CAGING CAPABILITY
+2° (9.0° GOAL)

CROSS ELEVATION AND LOS RANGE
15.5° VANGUARDED
20° UNVANGUARDED

TELESCOPE MOTIONS
ELEVATION RANGE
(OFFSET GUIDING)
LEVEL: 0.0 ARCSCE RMS
LEVEL: 0.15 ARCSCE RMS

TARGET ACQUISITION
(LONG-TERM JITTER)
POINTING STABILITY

TELESCOPE SYSTEM FUNCTIONAL REQUIREMENTS SUMMARY

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SOFIA
1.3 Study Objectives

The overall objectives of the in-house SOFIA Phase A Telescope System study were to establish feasibility of achieving the performance requirements within established system constraints (e.g., size, mass); and to develop a preliminary Telescope System cost estimate. Concurrently, a contracted effort with the same objectives was performed by Boeing Military Airplane Company (BMAC) for the aircraft system, with major emphasis on the cavity modification. The results of the BMAC study are fed back to the Telescope System to establish system constraints and define interfaces.

In order to achieve the Telescope System study objectives several steps were required. First, a review of the system performance requirements as established by the Science Consulting Group (SCG) was performed, including a flowdown of requirements and error budgeting exercise to establish subsystem requirements/constraints and boundaries. Next, subsystem conceptual designs were developed using the KAO configuration and existing technology where available and applicable, including alternate approaches if warranted. Detailed technical analyses, including model development, calculations and computer simulations, were then performed to determine performance capabilities of the candidate concepts, and to establish feasibility of meeting the requirements/constraints with the candidate designs. In cases where required performance was obviously not achievable, alternate design approaches were chosen with iteration of the analyses. Having established the "final" preliminary concepts, technology drivers and areas of concern were identified, where, for example, performance shortfalls still existed, sufficient information or modeling was not available, or further analysis was needed. The subsystem concepts were then integrated and reported out, in formats usable to establish preliminary system cost estimates, employing, for example, mass and complexity factors as cost model entering parameters. Cost estimates were then developed using various techniques and models (e.g., grass-roots, "RCA PRICE"), and uncertainties or ranges were factored in. A final systems engineering function was to define interfaces, assess the various concerns and uncertainties, and develop costs of alternative approaches. The risk assessment is to be used in an effort with Project Management to report back a "Project Position" on alternate system performance requirements (where necessary), which are felt to be achievable with acceptable risk. These will be iterated with the SCG to develop updated performance requirements for future project phases.
CHANGES TO PERFORMANCE REQUIREMENTS WHERE WARRANTED

Establish project position relative to requirements achievability and suggested

Define key subsystem and system interfaces

Establish preliminary cost estimates, including cost range due to uncertainties

Report on concepts, including mass-compartment factors to enter cost models

Prioritize technology drivers and areas of uncertainty or concern. requiring early

Follow-on emphasis to resolve

Identify technology drivers and areas of uncertainty or concern. requiring early

Iterate design concepts/develop different approaches as necessary

Reengineer/translate within given system constraints. using preliminary concepts

Perform detailed technical analyses to establish feasibility of achieving performance

Existing technology as starting point

Develop baseline system and subsystem concepts (and options) using KAA and

Performance requirements from requirement flowdown and error budgeting

Develop key subordinate subsystem requirements and error budgets from top-level

STUDY OBJECTIVES

Study objectives

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SOFIA
1.4 Observatory Overview

Major Elements

This section provides a top-level description of the SOFIA Observatory concept, as developed through in-house Phase A studies at ARC and contracted Phase A studies by Boeing Military Airplane Company (BMAC). Detailed technical descriptions are provided in Section 3 (Telescope System), Section 4 (Telescope Subsystems), Section 5 (Aircraft System), and Section 7 (Ground Support System).

For purposes of this overview description of the Observatory, the SOFIA concept is conveniently divided into the Aircraft System, Telescope System, and Ground Support/Operations System, which are briefly described in that order in the following pages. The Aircraft System consists of the basic aircraft, the cavity modification including door and Boundary Layer Control devices, and aircraft accommodations for the telescope, mission equipment and crew. The Telescope System encompasses the Telescope Assembly (optical subsystem, supporting structure, instrument mount/counterweight, and air bearing/vibration isolation system), and the Consoles and Electronics subsystem. Finally, the Ground Support/Operations System includes ground facilities, resources and equipment needed to support the aircraft, telescope, science instruments and investigators, and flight operations.
Investigations, Operations, Support

- Ground facilities, resources, and equipment for telescope, aircraft, instrument

- Ground support/operations system

- Telescope operation, mission management, and science investigation
  - Consoles and electronics subsystem, processors, controls, and displays
  - Instrument mount, structural isolation
  - Telescope assembly, optical subsystem, support structure, counterweight
  - Telescope system

- Basic aircraft, cavity modification, and equipment and crew accommodations

- Aircraft system

MAJOR ELEMENTS
SOFIA OBSERVATORY CONCEPT OVERVIEW

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Aircraft System Overview

The accompanying "Layout for Personnel Accommodations" (LOPA) was developed as part of a BMAC Phase A contracted study, using a Boeing 747SP (Special Performance) aircraft as the baseline SOFIA platform. The high-altitude/long endurance capabilities of this model, combined with its large cabin cross-section, make it the aircraft of choice to fulfill the SOFIA requirements. No other existing aircraft can rival this combination of attributes.

The LOPA depicts the configuration of the entire aircraft, telescope, and mission systems; larger drawing versions can be obtained from ARC on request. (A clearer three-page version is included in Section 5.) Main features include two full-depth pressure bulkheads forward of the wing, which isolate the cavity/cabin environments; the aft bulkhead mounts the telescope vibration isolators which support the entire air bearing/telescope/counterweight; the forward bulkhead contains an access door and telescope caging device. Two pressurized transfer tunnels pass beneath the telescope for personnel fore-aft transfer and systems routing (e.g., ducts, wiring, etc). Due to aircraft center of gravity constraints and cavity generated noise, all mission/science personnel and equipment are located in the aft section, behind a sound insulating partition; however, one science investigator console is located adjacent to the instrument/counterweight area, to provide instrument access and monitoring. Other aft mounted equipment includes air compressors (for the air bearing and vibration isolators) and liquid nitrogen tanks (for cavity precool/dehumidification). Standard aft-mounted galleys and lavatories, and the aft cargo compartment remain basically unchanged from the commercial aircraft. Aircraft power is distributed to all users from a panel located in front of the sound partition. The entire science mission payload is estimated to weigh just under 72,000 lbs, including ballast.
LAYOUT FOR PERSONNEL ACCOMMODATIONS (LOPA)
Cavity Concept

The diagram illustrates a 3.0 meter (primary mirror diameter) SOFIA telescope as it would be located in the cavity conceptualized by BMAC. The two telescope elevation extremes - 20° and 60° above horizontal - are shown; as can be seen, clearances are not generous. This cavity uses the existing floor location and outer skin configuration; cost would increase significantly to modify these geometries. The two-section, segmented cavity door is shown fully open at top and bottom; during operation, it would be open just enough to preclude telescope vignetting and would follow telescope elevation motion. Likewise, the BLC fence (shown separately), which protrudes in an arc outside and forward of the open port, will be segmented with separate actuators to allow telescope "following". Both of these provisions are needed to minimize drag, which impacts aircraft altitude and endurance capability. The open port extends past the aircraft centerline at top, and requires major structural strengthening, using skin doublers. Below the floor are depicted the two pressurized transfer tunnels, and the ground cooling system duct which runs from the cavity to the aircraft underbelly exterior. Aircraft control cables are also rerouted under the floor. This view is looking forward at the center of the telescope location in the cavity.
Telescope System Overview

Structure

The major structural components of the telescope system concept are shown. The structure must support the telescope optical components (mirrors) allowing minimal relative deflections under various loading and thermal conditions; allowable deflections, which include bending across the airbearing/support tubes, have been budgeted for structural design. Another major constraint is the system mass, where a goal of 30,000 lbs maximum (including air bearing and vibration isolation system) has been established. The structure must be large enough to support the 3 meter primary, while being sufficiently compact to fit within the aircraft cavity, considering all motions. Finally, the lowest natural frequency must be high enough to avoid resonance and control problems.

The basic structure features an optimized centerpiece which, due to its complex geometry and fabrication requirements, is baselined as 1/2 inch aluminum plate. A graphite-epoxy/aluminum sandwich cylindrical metering tube is envisioned, although a Serrurier strut arrangement is also viable. The headring/spider assembly provides stiff mounting for the chopping secondary mirror. Invar support tubes connect the telescope centerpiece to the airbearing rotor, and the rotor to the instrument flange/counterweight assembly, located in the aircraft cabin. The counterweight design has not been optimized; it is likely that a longer, narrower geometry will be preferable to minimize weight while balancing moments about the air bearing centerline. The bottom of the telescope is a removable "tub" which contains the primary mirror support system holding the mirror; the mirror must be recoated periodically in a separate facility. Likewise, the headring is removable to allow interchange of secondary mirrors.
CAVITY CONCEPT - REAR VIEW AT TELESCOPE CENTRELINE
Optical Configuration

The Telescope System optical layout is depicted, consisting of a "generic" Cassegrain configuration with provisions for instruments at the Cassegrain focus and Nasmyth focus. The latter is accommodated by use of a removable tertiary flat mirror which reflects the beam 90° aft through the air bearing. A possible arrangement uses two teriaries, the first dichroic to reflect the infrared beam while passing visible light to the second, which reflects to an offset fine guidance sensor mounted near the focal plane. Options for the exact optical form include a classical Cassegrain, a Ritchey-Chretien, and conceivably a "coma-compensated" design. The approximately f/1, 3-meter primary options include a frit-bonded "Ultra-Low Expansion" (ULE) quartz mirror (chosen for this study), a thin meniscus Zerodur design, or a spin-cast borosilicate design. The mirror is to be coated with vapor-deposition aluminum. The chopping secondary mirror concept is a "reactionless" design to minimize chopping vibrations imparted to the structure. Interchangeable secondary mirrors provide an f/11 Cassegrain focus, and f/13.5 and f/17 Nasmyth foct. Although a stationary tertiary is envisioned, an option requiring further evaluation is an active tertiary providing image motion compensation to the Nasmyth focal plane. Not shown are various sensors and devices needed for telescope operation, including inertial reference units (gyros), barrel-mounted acquisition and tracker cameras, primary mirror blower, primary mirror mount details, etc. These are described in later sections.
Telescope Support

The concept for supporting the SOFIA Telescope/counterweight is very similar to the successful KAO design, although scaled up to handle the increased size and mass. The three major elements shown are the air bearing, vibration isolation actuators, and telescope motion torquers. The air bearing is intended to provide a near-frictionless, three-axis rotating mount which accommodates unlimited elevation (aircraft roll axis) motion, and plus or minus 5° of "cross elevation" motions (pitch/yaw). It must also have at least a 31 inch "light path" inner diameter, accommodate the cabin/cavity pressure and temperature differentials, and preclude warm, compressed air from entering the cavity (with a scavenging system). A pressure seal system, which equalizes pressure on both sides of the bearing, is shown on the cavity side of the air bearing stator. Electromagnetic torquers are shown just outside of the air bearing; three sets of these in different locations provide the required 3-axis torquing used for target tracking, nodding, scanning, and slewing motions, plus field-rotation compensation. The vibration isolation system mount also uses compressed air, which is modulated to attenuate aircraft structure-borne vibration into the Telescope System. These pneumatic pistons are shown at top and bottom mounted to the aft cavity bulkhead; two more are located at each side of the air bearing in the current concept.
Telescope System Communications

The top-level communications block diagram depicts the interactions required amongst numerous mission and science operations elements; the system is similar to the KAO. On the left side are all the support sensors and actuators (except Telescope torquers) required for mission/science operation. The "cameras" include acquisition and tracking sensors, whose fields are displayed at the tracker operator console; the latter has a joystick for manual tracking, slewing, nodding, etc. Environmental "sensors" include cavity/telescope temperature, cavity dewpoint, pressure transducers, hygrometers, air data sensors, accelerometers, etc; "actuators" include primary mirror "blower," cavity heating/cooling controllers, compressors, etc. "Tracker support" sensors include telescope/cavity relative position sensors (TIPS), Aircraft Inertial navigation system (INS) attitude sensors, etc. Science/mission sensors include boundary layer control (BLC) fence positions, cavity door positions, instrument dewar cryogen level, instrument filter selection, etc.; "actuators" control these same devices. A central processor unit (redundant) is the central communications node and supervisory computer, linking peripheral devices and operator consoles via a local area network. The telescope pointing control system includes the cameras and inertial sensors (gyros), with links to TIPS and the aircraft INS; it integrates "error" inputs and joystick commands, into the tracking and stabilization loop controllers, and feeds the resulting pointing commands to the telescope torquers. The various manned consoles include: the tracker operator console, with a starfield display, joystick, keyboard and "mouse"; telescope operator/monitor console with a tracker (repeater) display, system status display and keyboard/mouse; mission manager console with a mission management display and system status repeater display, and keyboard/mouse; and the investigator consoles (main and remote) with a support computer, displays (e.g., tracker, experiment status, chopper), and keyboard/mouse controls.
TELESCOPE SYSTEM COMMUNICATIONS BLOCK DIAGRAM

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SOFIA
Telescope System Communications (Contd)

The SOFIA DMAC Subsystem is the Observatory data management, acquisition and communications network, with the design concept based on the KAO (with planned upgrades). Major requirements for the data/command system include: high reliability, with high mean time between failures and high noise immunity; redundancy, including a backup data central processor unit (CPU) available for immediate switchover, with stand-alone and network operation; modifiability/expandability, including standardization of hardware and communication protocols in a network concept; and communications requirements, with direct subsystem-to-subsystem data communication via a local area network (LAN - industry standard), network manager and test work station for network configuring and system maintenance, and capability for a hardwire (on-ground) link to ground based system simulators to increase efficiency of user integration. The design approach divides the SOFIA system into major subsystems, such as the secondary mirror, data CPU, telescope support systems, etc., and interconnects these subsystems through the broadband LAN. Each of the major subsystems consists of from one to seven elements, including the LAN interface, control unit, control panel/terminal, operating system, personal computer, drive electronics/motors, and diagnostic software, which are subsystem dependent. Proven/existing technology, hardware, software, and standardized systems are to be used as much as possible to reduce system complexity, maintenance, and cost, and to enhance expandability.
Miscellaneous Peripherals Equipment
Video Distribution
Broadband LAN
Cavity Environment
Network Manager/Test Work Station
Mission Manager
Video Signal Processing
Data CPU (with backup)

Housekeeping and Data Acquisition
Investigator Subsystem/Consoles
Telescope Support (Fence, Door, etc.)
Vibration Isolation
Telescope Inertial Pointing (Tips)
Star Tracker/Accommodation Cameras
Offset Guider (Focal Plane)
Secondary Mirror Assembly

- Major Subsystem Identification
- Interconnection through a LAN
- Division into Major Subsystems
- Concept
- Based on KAO with Upgrades
- Communications (data and voice)
- Modifiability
- Reliability/Redundancy
- Major Requirements

Data Management, Acquisition and Communications Subsystem

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SOFIA
Ground Support/Operations System

Ground Support Overview

The SOFIA Ground Support/Operations System element consists of the ground facilities, equipment, and personnel required to: operate and maintain the SOFIA aircraft; maintain, recondition and operate the Telescope System; select and schedule science investigations; support science teams and instruments at ARC; and plan and execute airborne science, and other missions. The figure depicts the support facilities concept for the Boeing 747 SP and Telescope System. Facilities required include: a "Nose-dock" hangar with access taxiway stressed for 800,000 lbs. and tow truck; mirror coating facility and equipment for Telescope optics removal/reinstallation and ground support (e.g., jigs, fixtures, cranes); ground-based cavity environmental control equipment; computer equipment for mission planning and science investigator/instrument support; SOFIA telescope simulator for instrument interface verification, and other assembly/test support equipment; miscellaneous aircraft and telescope maintenance equipment; offices for civil service, support contractor, and science investigator personnel (including navigation, flight planning and star chart room and astronomy reference library); storage facilities and investigator hygiene and rest accommodations; life support equipment maintenance and storage shop; and conference/briefing room(s). These facilities will be housed in the new buildings shown adjacent to the ARC flight ramp; space has been reserved for their construction, which will take place in the 1990-92 timeframe.
Ground Support/Operations System

Operations Overview

The SOFIA Observatory will be operated by NASA as a national facility with international collaboration and science investigations. The facility design is intended to provide compatibility with instruments/investigations developed for the KAO and, insofar as possible, with ground-based telescopes. State of the art facilities with adequate technical support staff are envisioned to provide a "user friendly" service, with considerations for human engineering (comfort, environment) for long duration observing flights. High operational reliability is required of the design to achieve yearly observation goals. The facility will be self-contained (with ground support equipment transportability) to provide operations from remote bases.

Operational goals for SOFIA include a 20-year useful lifetime with 120 research flights per year over a 40 week period. The remainder is to be used for telescope and aircraft maintenance, system modifications, pilot training and proficiency, and contingency time for make-up flights. Support service contractor staffing will handle day-to-day operations to the extent possible. A nine-month development/shake-down period is envisioned after system delivery before full operational capability is achieved, starting in FY 1992.

The research program involves science selection, observer funding and observatory scheduling during the operational period of each year. A formal science selection process will be carried out, starting with a "dear colleague" letter, submission of letters of intent and proposals, peer review and selection of investigations, and award announcements. Funding of U. S. Observers, who must submit cost plans, is by NASA grant through the ARC University Affairs Branch.
OPERATIONS OVERVIEW
GROUND SUPPORT OPERATIONS SYSTEM

SOFIA
SECTION II

SCIENCE

Introduction

2.1

2.2 Perspective on Modern Astronomy

2.3 Airborne Astronomy Background

2.4 SOFIA Comparison with KAO

2.5 Astronomical Promise

2.6 A Logical Progression

2.7 The Need for SOFIA
overall justifications for such a facility. Science.
The scientific background, the scientific potential, a comparison with other astronomy missions, and this report describes the first step of the recommended studies. This section presents the

This phase (IRAS) has led to the implementation of the recommendation coupled with the wealth of new infrared sources discovered by the infrared astronomical satellite

The unprecedented success of the KAO over the past thirteen years of operation, the 91 cm diameter infrared telescope that was later to be christened the Cerro P. Kuepper infrared

studies for a very large infrared telescope." At that time, the Agency was nearing completion of

In 1972 the Astronomy Survey (Greenstein) Committee Report to the National Academy of Sciences

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Perspective on Modern Astronomy
ENERGY DISTRIBUTIONS OF ASTRONOMICAL OBJECTS OBTAINED FROM THE LEARJET AND KUIPER AIRBORNE OBSERVATORIES
the fundamental phenomenon underlying the great success of space astronomy is the transmission of the electromagnetic spectrum over the Earth's atmosphere. The Earth's atmosphere is a filter that allows certain wavelengths to pass through while blocking others. However, there are several spectral regions where the transmission is poor, making observations difficult. These regions are the far-red and far-infrared, where the Earth's atmosphere is opaque.

The far-red region extends from 1.5 to 2.0 microns, and the far-infrared region begins at 5 microns. These regions are important for studying cool, dust-rich objects such as stars, planets, and galaxies. The far-red region is useful for observing the cool atmospheres of exoplanets and the far-infrared region is crucial for studying the cold, dense environments of galaxies and quasars.

The development of new observational techniques and instruments has allowed astronomers to extend their observations into these challenging regions. For example, the Spitzer Space Telescope and the Hubble Space Telescope have made significant contributions to our understanding of the far-infrared universe.

The most distant astronomical objects, such as quasars, are located in these regions, and their study has provided valuable insights into the early universe. The far-red and far-infrared regions are also important for understanding the processes that occur in the early stages of stellar and planetary formation.
FIGURE 2
ATMOSPHERIC TRANSMISSION VERSUS WAVELENGTH

- MANY WAVELENGTH BANDS OBSCURED FROM EARTH ARE ACCESSIBLE FROM AIRCRAFT
- MUCH IMPORTANT SCIENCE IS RESTRICTED TO THESE "FORBIDDEN" BANDS
star, which was the only observation of both immersion and emersion.

transient was made from the KH3 flying off the coast of Australia by stellar photometry of an occulted
observer larger of opportunity, and is readily "collected out." For example, the discovery of rings around
the background-limited sensitivity in the near infrared, (g) the observation can readily be deployed to
search the interior water in Orton at 1.6m. Other advantages of an airborne observatory
and the study of interior water in the discovery of water in Comet Hale-Bopp and Wilson in the 1-3 m range.

Some of the observations require the aircraft even at wavelengths where the transmission from the
Ground is totally accommodated with an airborne telescope.

Impossible from the Ground is totally accommodated with a ground telescope.

infrared from 4.0 to 7.0m. The lower plot shows that many of the absorbing water lines in the spectral range are still
im possible at the highest possible elevation.

The upper plot, particularly no work can be done from the Ground throughout the 3.0-5.0

Another point is that most of the water vapor in the line of sight is readily near the aircraft at

depending on altitude and season.

The water vapor pressure at the tropopause, which may be from roughly 30,000 to 50,000 feet altitude.

transient is lower than that pressure because the water is lessened mostly below the
albedo, altitude. This difference in pressure makes the water vapor pressure at the tropopause, which may
be from roughly 30,000 to 50,000 feet altitude.

The transmission from the ozone cutoff at about 0.65 microns or about one micron is dominated by
### Table 2

**Anticipated SOFIA Parameters (Compared with KAO)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SOFIA</th>
<th>KAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Flight profile:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Flight number</td>
<td>&gt;64, TBS</td>
<td></td>
</tr>
<tr>
<td>2. Flight duration (hr)</td>
<td>&gt;75</td>
<td>&gt;75</td>
</tr>
<tr>
<td>3. Flights per year</td>
<td>3</td>
<td>120</td>
</tr>
<tr>
<td>B. Optica</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Primary mirror diameter (meters)</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>2. Mirrored limit (degrees)</td>
<td>3 - 6</td>
<td>3 - 6</td>
</tr>
<tr>
<td>3. Telescope configurations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Astrometric field of view</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Available (a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Image quality of optics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Encouraged maximum power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Seeing limitations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Pointing stability (m. m. error)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Stabilized noise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Telescope parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D. Telescope performance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Pointing stability (m. m. error)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Stabilized noise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Telescope parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E. Infrared performance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Chopping performance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Thermal properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Sensitivity measured with dirty mirrors</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A related factor in the success of the airborne program is the extensive science community involvement.

A variety of scientific problems which can be studied from an airborne observatory is extremely diverse. Perhaps the most striking aspect of Figure 2 is its broad wavelength range. Observations from the KAO have actually been made at wavelengths separated by a factor of over 5000. This means that the

(continued)
TABLE 3
FOCAL PLANE INSTRUMENTS SCHEDULED FOR USE ON THE
KUIPER AIRBORNE OBSERVATORY IN FISCAL YEAR 1987

<table>
<thead>
<tr>
<th>INSTRUMENT TYPE</th>
<th>WAVELENGTH RANGE</th>
<th>SPECTRAL RESOLUTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>MULTICHANNEL SOLAR PHOTOMETER</td>
<td>30-350 µm</td>
<td>λ/Δλ = 3</td>
</tr>
<tr>
<td>HELIODYNME</td>
<td>150-500 µm</td>
<td>λ/Δλ = 2</td>
</tr>
<tr>
<td>GRATING</td>
<td>1.5 µm</td>
<td>λ/Δλ = 100</td>
</tr>
<tr>
<td>ECHELLE SPECTROMETER</td>
<td>30-120 µm</td>
<td>λ/Δλ = 2</td>
</tr>
<tr>
<td>PHOTOMETERS</td>
<td>40-200 µm</td>
<td>λ/Δλ = 2-10</td>
</tr>
<tr>
<td>GRATING</td>
<td>16-30 µm</td>
<td>λ/Δλ = 2-10</td>
</tr>
<tr>
<td>SPECTROMETER</td>
<td>30-50 µm</td>
<td>λ/Δλ = 2-10</td>
</tr>
<tr>
<td>MICHELSON INTEGRATING INTERFEROMETER</td>
<td>100-300 µm</td>
<td>λ/Δλ = 2-10</td>
</tr>
<tr>
<td>GRATING</td>
<td>2.5-5.5 µm</td>
<td>λ/Δλ = 2-10</td>
</tr>
<tr>
<td>SPECTROMETER</td>
<td>0.9-0.85 µm</td>
<td>λ/Δλ = 2-10</td>
</tr>
<tr>
<td>GRATING</td>
<td>0.4-0.35 µm</td>
<td>λ/Δλ = 2-10</td>
</tr>
<tr>
<td>SPECTROMETER</td>
<td>0.3-0.25 µm</td>
<td>λ/Δλ = 3</td>
</tr>
<tr>
<td>GRATING</td>
<td>0.1-0.05 µm</td>
<td>λ/Δλ = 3</td>
</tr>
<tr>
<td>SPECTROMETER</td>
<td>0.15-0.1 µm</td>
<td>λ/Δλ = 3</td>
</tr>
<tr>
<td>GRATING</td>
<td>0.05-0.01 µm</td>
<td>λ/Δλ = 3</td>
</tr>
<tr>
<td>SPECTROMETER</td>
<td>0.01-0.005 µm</td>
<td>λ/Δλ = 3</td>
</tr>
</tbody>
</table>

PRINCIPAL INVESTIGATOR/INSTITUTION

| E. BECKLING, UNIVERSITY OF MAHI | A. BECK, UNIVERSITY OF CALIFORNIA AT BERKELEY |
| J. D. BURGESS, NASA/AMES RESEARCH CENTER |
| A. E. CHENIE, NASA/AMES RESEARCH CENTER |
| D. A. HARPER, YERKES OBSERVATORY |
| P. M. HARRIS, UNIVERSITY OF TEXAS AT AUSTIN |
| T. J. HERRETT, CORNEL UNIVERSITY |
| R. H. HILDEBRAND, UNIVERSITY OF CHICAGO |
| H. F. LARSON, UNIVERSITY OF ARIZONA |
| H. MOSELEY, NASA/GODDARD |
| T. G. PHILLIPS, UNIVERSITY OF CALIFORNIA AT BERKELEY |
| J. F. ROSE, NASA/AMES RESEARCH CENTER |
| P. C. VANDERWOUDE, CALIFORNIA 
   AT BERKELEY |
| J. K. WILSON, HELL LABS |
| K. C. WITTROCK, NASA/AMES RESEARCH CENTER |
Background and challenges:

SOFIA, the requirement of a lightweight primary mirror to permit the sample, much more rapid cold-down prior to flight.

- Item B.7: Thermal system enables an essential feature for SOFIA, the reflector large secondary mirror (about 30 cm diameter) will require a well-designed chopper.

- Item D.2: Elevation range: The lower range for SOFIA means that sources farther south than the Galactic center will be readily accessible on nights of high see-through. In Table 2, elevation range is highlighted.

- Item A.3: Flight per year. It is felt by the science community that every effort should be made to permit SOFIA to be operated at the 120 flights/year level. This rate is understood to be achievable for SOFIA. A few of these are highlighted here: Table 2 summarizes these parameters expected to be achievable for SOFIA, and compares them with the KAO.
FIGURE 3
CIRCUMSTELLAR DISKS AROUND LOW MASS STARS

KAO OBSERVATIONS AT 47 AND 95 μm OF THE SOURCE SVS 13 IN NGC 1333. THE CIRCLES REPRESENT THE DIFFRACTION LIMITED BEAM SIZE FOR A 3m APERTURE TELESCOPE.

SOFIA CAN PROVIDE SPATIAL RESOLUTION AND SENSITIVITY INCREASES OVER KAO THAT WILL ALLOW:

- DISCRIMINATION BETWEEN THIN AND THICK DISKS.
- OBSERVATION OF A STATISTICALLY SIGNIFICANT NUMBER OF SUCH DISK-LIKE SOURCES.
- DETERMINATION OF TEMPERATURE PROFILES ACROSS THE DISKS.
- DIRECT OBSERVATIONAL TESTS OF PROTOSTELLAR DISK MODELS.
structure, chemical makeup, and magnetic fields in these regions. When the combined observations are

Atmospheric models

Propositions models.

spectrometer mounted at SOFIA's coronal plane. In addition, SOFIA's good spatial resolution may help to provide a weak signal from individual emission lines, but one that could be detected with a high signal-to-noise ratio. The redshift at these wavelengths is likely to escape unobserved. Fortunately, the redshift of all potential targets is lower than 100 km/s and is likely to escape unobserved. Fortunately, the redshift of all potential targets is lower than 100 km/s and is likely to escape unobserved. Fortunately, the redshift of all potential targets is lower than 100 km/s and is likely to escape unobserved.

Star formation, as currently understood, begins with a dense, dusty, gas-rich region in

Suitably instrumented, SOFIA will provide images or spectra of a vast variety of fundamental

...
FIGURE 4
VELOCITY RESOLVED SPECTRA OF GALACTIC CLOUDS
(C II) 1900.537 GHz

KAO OBSERVATIONS OF THE 158 µm C+ LINE. THE MEASUREMENT REVEALS CLOUD COOLING RATE, GAS DYNAMICS, AND CARBON CHEMISTRY.

SOFIA WOULD

- PERMIT MAPPING TO DETECT INDIVIDUAL CLUMPS OR IONIZATION FRONTS, PROBING THE NATURE OF OBSCURED LUMINOSITY SOURCES.

- ALLOW C ABUNDANCE ESTIMATES IN OTHER OBJECTS (e.g. PLANETARY NEBULAE, LATE STELLAR ENVELOPES) TOO FAINT FOR OBSERVATIONS FROM THE KAO.
systematic uncertainties associated with the publication. In the last 6 years, SOPHIA could make the same measurement on a single object, eliminating the spatially resolved, the spectrum had to be obtained by subtracting spectra of the reference system, but not be the IR interstellar spectrum of the ions measured from the KAO. Because the rings could not be present, plus to be resolved by other, similar telescopes, such as SIRTF of the KAO. Figure 6 shows the example of the Phoebe Ring, which are lines of closest to the atmosphere in the spectra of the planets and permit the study of detailed images of planets will be obtained at much higher spatial and angular-Far-infrared and submillimeter images of planets will be obtained at much higher spatial and angular-resolution than is available from current spacecraft. These will provide new understanding of the planetary rings, the largest disk material and its relationship to the planet's solar system. Would also be prime targets for SOPHIA, from which near-infrared observations should arise to study planetary atmospheres and ring systems. Comets, the least understood objects in the solar system, would also be prime targets for SOPHIA. Observations made at near-infrared, visible, and near-ultraviolet wavelengths will be made of protostars and protoplanets of nearby objects, which are too faint for ground-based observations. In other objects, such as young planetary nebulae or late-type stellar envelopes, which are too faint for ground-based observations, one could detect individual clouds of material for comparison with the maps of the inner region of protoplanetary nebulae. SOPHIA would provide more detailed information about the distribution of material within the planet.
FIGURE 5
FAR INFRARED SPECTROSCOPY OF IR-BRIGHT GALAXIES

KAO MEASUREMENT OF O\textsuperscript{++} IN THE STARBURST GALAXY M82.

RADIO MAP OF M82 NUCLEUS SHOWING KAO & SOFIA BEAMS.

- IR LINES MEASURE EXCITATION, DENSITY, ABUNDANCE RATIOS THROUGHOUT THE VOLUME SAMPLED.

- SOFIA WOULD PERMIT:

INDEPENDENT EXAMINATION OF DISTINCT RADIO COMPONENTS.

MEASUREMENT OF A LARGE SAMPLE OF IRAS GALAXIES.
reduce the background and so leads to higher sensitivity. Lower resolution instruments take better
some unidentified echos that are not yet fully understood. In Figure 6, the ambient temperature of the telescope's
antennas and feed units is shown as a function of wavelength in Figure 8. For the digitized, spectral resolution
parameters, see Figure 5. The horizontal line represents the sensitivity of the antenna and feed units, whereas the

Figure 7 is a plot of photometric sensitivity for SOFIA and SIRTF, respectively. For point source detection versus wavelength, we now
examine the role of NAGA, a test of existing and planned astrometry programs.

Having established the science potential for SOFIA based on its anticipated performance, we now
FIGURE 6
COMPOSITION AND STRUCTURE OF PLANETARY RING SYSTEMS

KAO Spectrum of Thermal emission from Saturn's rings

- Far infrared KAO spectrum suggests small particle constituent

SOFIA would permit:
- Spectroscopy of the rings on a routine basis to study composition
- Observation of stellar occultations to determine the structure with ~1km resolution
It is clear that SOFIA is a natural and important element in the overall progression of NASA's Astronomy and Astrophysics observatories. This is especially true for IRAS, which set the stage for the space observatories that followed. It is clear that SOFIA would allow detailed infrared studies to be performed from the ground, which is a key advantage of SOFIA.

SOFIA's role as the stepping stone to IRIS and LDR was mentioned above. As a facility which is cryogenically cooled, it is not possible to achieve the same level of sensitivity as a full resolution space observatory. However, SOFIA can still make valuable contributions to the science. Its ability to detect faint sources at greater distances and provide higher resolution images makes it an important complement to IRIS and LDR.

SOFIA could detect all of the survey point sources, whereas the KAO can detect only about 15 percent of the faintest sources. In volume of space near a compact source, it would be 10 times more sensitive. Due to the 100 times faster rotation, SOFIA would be able to detect fainter sources. Assuming a 2-meter aperture, SOFIA would be able to detect a major advance over the current state of the art.

From the fore-going technical considerations, it is clear that SOFIA would make it a valuable complement to IRIS and LDR. The character of SOFIA will make it a valuable complement to IRIS and LDR. If development is not started promptly, SOFIA could be out of the game before it even begins.

The operation of the SOFIA interferometer is still in the planning stage, and SOFIA will be designed as a precursor to these facilities. The key advantage of SOFIA is that it will allow for the reduced background provided by cryogenically cooled telescopes. For example, the advantage of the reduced background provided by cryogenically cooled telescopes, such as those used by LDR, is expected to be the major benefit of SOFIA.
FIGURE 7
PHOTOMETRIC SENSITIVITY

\(1 \sigma, \Delta \Omega \Delta \lambda = \lambda ^3\)

Scaled from KAO assuming emissivity is reduced to 0.15 (telescope) + 0.12 (sky). SOFIA assumed to have a 3.0 m primary.
many of the difficulties associated with space missions. Tremendous potential for science which cannot be done from earth, while remaining uncumbered by prompt response to experimental scientific opportunities. Truly, SOFIA would be a facility with assures broad community involvement, rapid implementation of new focal plane technologies, and annual peer review with a short turn-around time. From on a reusable, "launch" vehicle. In space performance SOFIA is an observatory class facility, readily accessible to the science community.

A Large Propulsion (contd)
FIGURE 8
ANGULAR RESOLUTION

SOFIA
The need for an Interim Facility leading to the spectroscopic 8 meter FIRST and 20 meter class IRD anticipated in the first decade of the 21st century.

The need for increased sensitivity at high spectral resolution, and

The need for higher angular resolution at infrared wavelengths which are inaccessible from the ground will not be met and any other observatory foreseen in this century will not be able to do so.

The above discussion confirms that SOFIA will satisfy the following critical needs in astronomy which

The need for FORSIA is

The need for

The need for increased sensitivity at high spectral resolution, and

The need for higher angular resolution at infrared wavelengths which are inaccessible from the ground.
FIGURE 9
SPECTRAL RESOLVING POWER

![Graph showing spectral resolving power with various instruments like HST, KAO, SOFIA, SIRTF, and LDR.](image-url)
needed to take its place among the world's unique astronomical facilities. Support preparations for planned far-infrared and submillimeter space astronomy missions. SOFIA is thus, it is clear that SOFIA will provide a rich harvest of astronomical results, and concurrently meet the expected demand for a larger ground-based telescope would be well aware that one in existence had a .9 meter aperture. To put the project in perspective, one has only to remember that the .9 meter KAO telescope is the wave-length coverage from the near ultraviolet to the infrared wavelengths, and deployability for observations of ephemeral events such as comets, eclipses, occultations, and novae. In addition to fulfilling these needs, SOFIA would retain the unique features of its predecessors: program well into the 21st century.

However, the discipline needs to be further strengthened to undertake a project of the size of LDR.

The Need for SOFIA (cont'd)
Figure 10

AIRBORNE AND SPACE IR ASTRONOMY OPERATIONAL SYNOPSIS

Ames Research Center

SOFIA
TeleScope System Description

3.0
TELESCOPE SYSTEM SUMMARY - SCOPE

- CONFIGURATION SUMMARY
  - TELESCOPE "SUBSYSTEM" (OPTICAL ASSEMBLY/STRUCTURE); MAJOR TRADES
  - CONTROL/COMMUNICATIONS SYSTEM
  - MISCELLANEOUS COMPONENTS

- BUDGETS AND CONSTRAINTS
  - REQUIREMENTS FLOWDOWN
  - TOP-LEVEL OPTICS/POINTING BUDGETS
  - VOLUME AND MASS CONSTRAINTS/BUDGETS; STATUS

- INTERFACES
  - BLOCK DIAGRAM (TOP-LEVEL)
  - COMPONENT INTERFACES

- CONCLUSIONS
  - KEY FINDINGS/FEASIBILITY
  - MAJOR SYSTEM ISSUES
shown. This system isolates actuator structure-determinate vibrations from the telescope structure.

Vertically actuators for the pneumatic vibration isolation system, the rotational actuators are not required. A pair of differentials across the air bearings, finally, external to the torque arms, allow for pointing control. On the cavity side of these torque arms is a pressure-equalization device to eliminate the forces acting on the cavity, just outside of the air bearings. For telescopes

Telescope elevation range and x 5 cross-elevation/LOS motion. The optical element, supported by the telescope structure, consists of the two-section mirror located below the primary mirror. The Cassegrain instrumentation would mount mirrors (system f/1.7 Cassegrain) and a focal length tertiary mirror (not shown) to direct the beam 90° aft to a Nasmyth instrument. A Cassegrain instrument would mount mirrors (system f/1.7 Cassegrain) and a focal length tertiary mirror (not shown) to direct the beam 90° aft to a Nasmyth instrument. A Cassegrain instrument would mount mirrors (system f/1.7 Cassegrain) and a focal length tertiary mirror (not shown) to direct the beam 90° aft to a Nasmyth instrument.

The chart illustrates the physical layout of the telescope "subsystem" concept (optical, counterweight, and structure), as mounted on the tilt table platform in a modeled beam, 747-S. The optical and structure, as mounted on the tilt table platform in a modeled beam, 747-S.
I/O loads, and external sensors to preclude "ballot fixing" during hand (or crash) landings.

The current bearing concept is a spherical air bearing (scaled up KAO type) requiring 46 standard 1ST and CCD types.

Chopping requirements.

The Telescope Pointing and Control System tolerances are similar in design to the KAO system, utilizing 4-axis chopping requirements 50 - Newton actuators, and a -225 Hz bandwidth controller to meet the

The Telescope Pointing and Control System tolerances are similar in design to the KAO system using 4-axis chopping requirements 50 - Newton actuators, and a -225 Hz bandwidth controller to meet the
# TELESCOPE DESIGN SUMMARY

<table>
<thead>
<tr>
<th>MASS GOAL</th>
<th>30,000 LBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPTICS</td>
<td>CASSEGRAIN, 1/11-1/18 SYSTEM</td>
</tr>
<tr>
<td>PRIMARY</td>
<td>3.0 M DIA...1/1...ULE...110 Kg/SQ. M. (FACESHEET)</td>
</tr>
<tr>
<td>PRIMARY SUPPORT</td>
<td>G/E...ACTIVE PNEUMATIC 48 PT AXIAL AND 12 LATERAL SUPPORTS</td>
</tr>
<tr>
<td>SECONDARY</td>
<td>GLASS</td>
</tr>
<tr>
<td>CHOPPER</td>
<td>FULL 2 AXIS ELECTROMAGNETIC...50 N ACTUATOR 225 Hz BW</td>
</tr>
<tr>
<td>STRUCTURE</td>
<td>ALUMINUM/G/E HYBRID METERING TUBE</td>
</tr>
<tr>
<td>TORQUERS</td>
<td>SEGMENTED SPHERICAL MAGNETIC</td>
</tr>
<tr>
<td>GYROS</td>
<td>GAS BEARING RATE INTEGRATING</td>
</tr>
<tr>
<td>CAMERAS</td>
<td>ISIT AND CCD</td>
</tr>
<tr>
<td>AIRBEARING</td>
<td>SPHERE, 5 DEG ROTATION AZIM/LOS 40 SCFM/265 PSIA...DIA = 48&quot;  AIR GAP = .00096&quot;</td>
</tr>
<tr>
<td>VIB ISOLATION</td>
<td>AIR SPRINGS...INTERNAL SNUBBERS</td>
</tr>
</tbody>
</table>

3 - 7
should be demonstrated.

After reviewing many concepts it all still appears that a KNO-1 type of bearing is most promising, but it
when attached to the instrument frame in the telescope, a major trade was the support system.
(cylindrical) lenses, were opposed to ball bearings or any rotors, and appear to be more effective.
primary mirror temperature control will require forced gas blowing to minimize the time constant.

The secondary mirror Chopper was found not to require a reelevation design. A reeelevation design.

The second mirror chopper was found not to require a reelevation design. A reeelevation design.

The telescope meteering structure material was selected several times, with 

loop is energized.

driver piston, piston force will be controlled by a programmed routine, and no feedback control

condition (2.5) elevation angle, is energized as an active support system employing pneumatically

mounting subsystem, which must control mirror position and surface elevation over changing load.

The multi-gouge mirror extension of the telescope used on the Hubble Space Telescope is shown in this figure. The displacement

extension of the telescope used on the Hubble Space Telescope is shown in this figure. The displacement

A component of overall importance and technology complete for SOFI is the -3.0 meter./1.5

The major trade-offs are shown on the chart with the concepts selected written in legend. More details are

Many alternative concepts were analyzed for the various elements of the telescope system. Some of
MAJOR TRADES

<table>
<thead>
<tr>
<th>MIRROR MATERIAL</th>
<th>BORO. SIL. vs. ULE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>STRUCTURED VS MEMBRANE</td>
</tr>
<tr>
<td>MIRROR MOUNT</td>
<td>ACTIVE vs PASSIVE</td>
</tr>
<tr>
<td>TELESCOPE STRUCTURE</td>
<td>INVAR-G/E-AL/-HYBRID</td>
</tr>
<tr>
<td></td>
<td>TUBE VS TRUSS</td>
</tr>
<tr>
<td>CHOPPER</td>
<td>REACTIONLESS vs UNBALANCED</td>
</tr>
<tr>
<td></td>
<td>SINGLE vs TWO AXIS</td>
</tr>
<tr>
<td>THERMAL CONTROL</td>
<td>PASSIVE-vs FORCED GAS BLOWING</td>
</tr>
<tr>
<td>GYROS</td>
<td>TYPE</td>
</tr>
<tr>
<td>AIRBEARING</td>
<td>LOCATION:ON TELESCOPE vs INST.</td>
</tr>
<tr>
<td></td>
<td>SPHERICAL vs MULTIPOINT</td>
</tr>
</tbody>
</table>
planned configuration are provided in Section 4.5. Test work stations to provide network configuration and system maintenance. Further details of the
Test Work Stations to provide network configuration and system maintenance. Further details of the
Test Work Stations to provide network configuration and system maintenance. Further details of the
test work stations to provide network configuration and system maintenance. Further details of the
test work stations to provide network configuration and system maintenance. Further details of the
test work stations to provide network configuration and system maintenance. Further details of the
test work stations to provide network configuration and system maintenance. Further details of the

DATA MANAGEMENT, ACQUISITION AND COMMUNICATIONS SYSTEM CONCEPT

- REQUIREMENTS
  - HIGH RELIABILITY
  - REDUNDANCY
  - MODIFIABILITY/EXPANDABILITY
  - NETWORK-INDUSTRY STANDARD
  - COMMERCIAL/OFF-THE-SHELF COMPONENTS

- DESIGN GUIDELINES
  - USE KAO AS SYSTEM MODEL
  - INCORPORATE PLANNED KAO UPGRADES AND ADDITIONAL ENHANCEMENTS
  - UTILIZE NETWORK CONCEPT FOR DIRECT DATA COMMUNICATIONS
  - ADD BACKUP DATA CPU
  - STANDARDIZED HARDWARE AND COMMUNICATIONS PROTOCOL
  - ADD GROUND STATION LINK TO ENHANCE USER INTEGRATION
  - ADD NETWORK MANAGER FOR NETWORK CONFIGURING
  - ADD TEST WORK STATION FOR ENHANCED MAINTENANCE
Section 4.5: A more detailed description of the system elements and services used is provided in Section 3.4, “Interfacing.”
DATA MANAGEMENT, ACQUISITION AND COMMUNICATIONS SYSTEM
MAJOR ELEMENTS

HOUSEKEEPING AND DATA ACQUISITION SUBSYSTEM
DATA CPU SUBSYSTEM AND BACKUP
TELESCOPE SYSTEM SUPPORT SUBSYSTEM
PRINCIPAL INVESTIGATOR SUBSYSTEM
MISSION MANAGER WORK STATION
TELESCOPE OPERATOR WORK STATION
TRACKER SYSTEM OPERATOR WORK STATION
NETWORK MANAGER AND TEST WORK STATION
REMOTE P.I. WORK STATION
BROADBAND LOCAL AREA NETWORK

MISC. PERIPHERAL EQUIP. (E.G., SENSORS/ACTUATORS)
CAVITY ENVIRONMENTAL CONTROL SUBSYSTEM INTERFACE
VIDEO SIGNAL PROCESSOR SUBSYSTEM INTERFACE
VIBRATION ISOLATION SUBSYSTEM INTERFACE
TELESCOPE INERTIAL POINTING SUBSYSTEM INTERFACE
ACQUISITION/STAR TRACKER SUBSYSTEM INTERFACE
OFFSET GUIDER SUBSYSTEM INTERFACE
OSCILLATING SECONDARY MIRROR SUBSYSTEM INTERFACE
VIDEO DISTRIBUTION SUBSYSTEM INTERFACE
GROUND BASE SYSTEM AND SYSTEM LINK
Control loops, but are also displayed for monitoring purposes. Perturbation rejection, vibration isolation, and fine balancing are performed automatically, with feedback (FB) stabilization. The current SDOA concept (by automatic video tracking system) functions such as Telescopic Operator (TO) target acquisition and tracking can be performed manually by the Telescopic Operator or automatically (in larger or longer complex environments). Manual operation by the Telescopic Operator may be activated controlled by either the Telescopic Operator or the Experiment. The Experimenters' Telescopic Carriage may be activated controlled, for example, by the Experiment (video). This is controlled by the Experiment Carriage's secondary mirror changer and focus can be displayed at the Experiment. The Experiment's Workstation, the Experiment (video) is controlled by the Experiment Carriage's secondary mirror changer and focus can be displayed at the Experiment. Some displays/indicators are shared by two or more workstations, or may be manually controlled. The functions are controlled/displayed at either the Experiment Operator Workstation, the Mission Operator Workstation, the Mesasurement Workstation, or the Experiment (video). The Experiment (video) is shared by all functions requiring front panel controls for acquisition, display, or identification of the type of control control system is given in the front for front panel (console/monitor). The chart lists the SDOA Telescopic and Mission System functions which require control and/or monitoring by mission operators or Experimenters personnel. For each functional element, control and monitoring are also displayed for monitoring purposes.
## CONTROL AND MONITORING SYSTEMS

<table>
<thead>
<tr>
<th>CONTROL SYSTEM TYPE</th>
<th>FRONT PANEL CONTROLS</th>
<th>FRONT PANEL DISP/INDIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOUNDARY LAYER FENCE CONTROL</td>
<td>DISP CNTL W/ BRAKE</td>
<td>X</td>
</tr>
<tr>
<td>COARSE TELESCOPE ELEV CONTROL</td>
<td>DISP CNTL W/ BRAKE</td>
<td>X</td>
</tr>
<tr>
<td>APERTURE DOOR</td>
<td>DISP CNTL W/ BRAKE</td>
<td>X</td>
</tr>
<tr>
<td>APERTURE SHIELD</td>
<td>OPEN CLOSE W/ BRAKE</td>
<td>X</td>
</tr>
<tr>
<td>PRESSURE WINDOW WHEEL</td>
<td>DISP CNTL W/ BRAKE</td>
<td>X</td>
</tr>
<tr>
<td>TELESCOPE AUTO BALANCE</td>
<td>DISP CONTROL</td>
<td>X</td>
</tr>
<tr>
<td>TELESCOPE SYSTEM ACTIV/SHUTDN</td>
<td>DISCRETE LOGIC</td>
<td>X</td>
</tr>
<tr>
<td>TELESCOPE STABILIZATION</td>
<td>CMPLX FB CNTL</td>
<td>X</td>
</tr>
<tr>
<td>TARGET ACQ &amp; TRACKING</td>
<td>CMPLX FB CNTL</td>
<td>X</td>
</tr>
<tr>
<td>CHOPPER DRIVE</td>
<td>CMPLX ANLG/DIG FB</td>
<td>X</td>
</tr>
<tr>
<td>SECONDARY MIRROR FOCUS</td>
<td>DISP CONTROL</td>
<td>X</td>
</tr>
<tr>
<td>MECH OFFSET POINTING</td>
<td>DISP CONTROL</td>
<td>X</td>
</tr>
<tr>
<td>TELESCOPE AUTO CENTERING</td>
<td>ACTIVATION LOGIC</td>
<td>X</td>
</tr>
<tr>
<td>TELESCOPE CAGING</td>
<td>ACTIVATION LOGIC</td>
<td>X</td>
</tr>
<tr>
<td>AIR BEARING</td>
<td>ACTIVATION LOGIC</td>
<td>X</td>
</tr>
<tr>
<td>TELESCOPE ATTITUDE READOUT</td>
<td>ACTIV LGC/ANLG/DIG</td>
<td>X</td>
</tr>
<tr>
<td>TELESCOPE SYSTEM FAULT ANNUNC</td>
<td>DISCRETE LOGIC</td>
<td>X</td>
</tr>
<tr>
<td>SYSTEM INTERCOM</td>
<td>AUDIO</td>
<td>X</td>
</tr>
<tr>
<td>VIDEO DISTRIBUTION</td>
<td>VIDEO SWTC HG</td>
<td>X</td>
</tr>
<tr>
<td>EXPERIMENTER POWER DIST</td>
<td>DISTRIBUTION LOGIC</td>
<td>X</td>
</tr>
<tr>
<td>VACUUM SYSTEM</td>
<td>ACTIVATION LOGIC</td>
<td>X</td>
</tr>
<tr>
<td>VIBRATION ISOL SYSTEM</td>
<td>COMPLEX FB CNTL</td>
<td>X</td>
</tr>
</tbody>
</table>

3-15
requirements flowdown

3.3

System Budgets and Constraints
REQUIREMENTS FLOWDOWN - EXAMPLE
Section 4. Concerned secondary. Detailed error budgets are contained in the respective subsystem descriptions in Appendix A. Instrumental errors are categorized into the following groups: "plotter errors", "plotter mounting errors", "lightning errors", and "lightning mounting errors". Another more stringent budget has been developed for the 2-meter aperture spot size requirement. The contributions from the optics (mirrors, window) are neglected. The system performance in the range of 1 micron (inherent) is the effect of seeing. The wavefront error budget for position error due to wind, and the SOPA pointing and control system ("wavefront errors") are both budgets are detailed. The chart shows the first tier of error budgets developed for the telescope optical assembly.
TRACKING AND WAVEFRONT ERROR BUDGETS

TELESCOPE WAVEFRONT ERROR BUDGET - 3 M APERTURE

- TELESCOPE
  - OPTICS
    - PRIMARY MIRROR 0.42 µm
    - SECONDARY MIRROR 0.19 µm
    - TERTIARY MIRROR 0.15 µm
- FOCUS 0.87 µm
- ALIGNMENT 0.39 µm

AV = 0.38 µm
A.D.L. = 14 x RMS WFE
= 14.4 µm RMS

TRACKING SYSTEM ERROR BUDGET

- Focal Plane
  - Tracking Error
    - 0.15 arcsec RMS

- A/C Excursions 0.06 arcsec RMS
- A/C Vibration 0.08 arcsec RMS
- Thermal Shift 0.03 arcsec RMS
- Aerodynamic Loading 0.1 arcsec RMS
- Sensor and Electronic Noise 0.03 arcsec RMS
Telescope diameter must be reduced. Tradeoffs are continuing in these areas, and close coordination will be needed. Telescope diameter is an issue as well; in mind, otherwise the cross-elevation/loss elevation range, and/or the higher elevation may cause structural interference. Furthermore, the vibration isolation system will have to be designed to accommodate this under future conditions. Also, the specification calls for an elevation range of 15-75° with vibration isolation system degradation. The current position of the Telescope (under future conditions) is those environments are allowable, while the current science requirement is secondary mirror mechanism. As can be seen, the Telescope head is horizontal. As seen, the Telescope head is at an extreme elevation position of 90° and 60° above the current elevation position. If the current elevation is not reduced in size, also, the current science requirement is met. Telescope, provided by ABC, is shown at its extreme elevation positions of 90° and 60° above the current elevation position. The chart shows the current science requirement at the Telescope center elevation position.
TELESCOPE VOLUME/GEOMETRY CONSTRAINT
Telescope Mass Budget and Status
## Telescope Mass Budget and Status - LBS

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Original Budget</th>
<th>Current Budget</th>
<th>Current Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. AIR BEARING</td>
<td>7,000</td>
<td>13,500</td>
<td>17,900</td>
</tr>
<tr>
<td>2. VIBRATION ISOLATION SYSTEM</td>
<td>3,000</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>3. INSTRUMENT/COUNTERWEIGHT (INCL. GYROS)</td>
<td>10,000</td>
<td>6,900</td>
<td>8,500</td>
</tr>
<tr>
<td>4. TELESCOPE (OPTICS) STRUCTURE</td>
<td>3,850</td>
<td>250</td>
<td>200</td>
</tr>
<tr>
<td>5. CENTERPIECE SUPPORT STRUCTURE</td>
<td>2,000</td>
<td>5,600</td>
<td>5,600</td>
</tr>
<tr>
<td>6. PRIMARY MIRROR</td>
<td>1,500</td>
<td>1,500</td>
<td>1,680</td>
</tr>
<tr>
<td>7. PRIMARY MIRROR MOUNT AND COOLING</td>
<td>1,500</td>
<td>1,000</td>
<td>1,200</td>
</tr>
<tr>
<td>8. SECONDARY MIRROR</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>9. SPIDER/HEADRING</td>
<td>450</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>10. CHOPPER MECHANISM</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>11. CAMERAS (TRACKER, ACQ.)</td>
<td>500</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>30,000</strong></td>
<td><strong>30,000</strong></td>
<td><strong>36,310</strong></td>
</tr>
</tbody>
</table>
The weight and performance are provided in Section 5. Incremental capability in the current configuration is 5.5 hours at FL410. Further details of aircraft increments, such as increased performance or boost of thrust engines, and/or reduce the modification drag in order to meet the standard aircraft endurance at altitude requirements, the aircraft is to some degree is accounted for by air-conditioned equipment, including consoles, including tanks. The ballast required for this configuration is deemed weight to be added in the fuel area. The weight of the cavity modification has grown from 12,700 lbs due to matching the baseline telescope.
### SOFIA PAYLOAD MASS BUDGET

<table>
<thead>
<tr>
<th>ITEM</th>
<th>MASS, LB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. TELESCOPE SYSTEM (TELESCOPE, INSTRUMENT/ COUNTERWEIGHT, VIBR. ISOL. SYSTEM/AIR BEARING)</td>
<td>30,000</td>
</tr>
<tr>
<td>2. CAVITY MODIFICATION (BULKHEADS, DOOR, BLC, ETC.)</td>
<td>16,000</td>
</tr>
<tr>
<td>3. PNEUMATIC SYSTEM</td>
<td>2,000</td>
</tr>
<tr>
<td>4. NITROGEN SYSTEM</td>
<td>1,500</td>
</tr>
<tr>
<td>5. DATA ACQUISITION/MANAGEMENT SYSTEM AND INTERFACE</td>
<td>1,750</td>
</tr>
<tr>
<td>6. CONTROL CONSOLES/EQUIPMENT RACKS</td>
<td>3,000</td>
</tr>
<tr>
<td>7. VACUUM SYSTEM</td>
<td>700</td>
</tr>
<tr>
<td>8. CAVITY ENVIRONMENTAL CONTROL SYSTEM</td>
<td>750</td>
</tr>
<tr>
<td>9. AFT GALLEY</td>
<td>1,500</td>
</tr>
<tr>
<td>10. CREW AND PASSENGERS</td>
<td>1,800</td>
</tr>
<tr>
<td>11. SAFETY EQUIPMENT</td>
<td>1,000</td>
</tr>
<tr>
<td>12. SEATS (40)</td>
<td>1,000</td>
</tr>
<tr>
<td>13. AFT LAVATORY</td>
<td>385</td>
</tr>
<tr>
<td>14. FOOD AND WATER</td>
<td>400</td>
</tr>
<tr>
<td>15. BALLAST</td>
<td>10,020</td>
</tr>
<tr>
<td><strong>TOTAL PAYLOAD:</strong></td>
<td><strong>71,805</strong></td>
</tr>
</tbody>
</table>

| FERRY FLIGHT:  ADD: 31 PASSENGERS                                   | 6,200    |
| MISC. CARGO                                                          | 46,520   |
| **TOTAL:**                                                          | **52,720** |

(TOTAL 124,525)
MAJOR INTERFACES

- ELEMENTS
  - AIRCRAFT SYSTEM
  - TELESCOPE ASSEMBLY
  - CONSOLES AND ELECTRONICS SUBSYSTEM
  - GROUND SUPPORT SYSTEM

- INTERFACES
  - STRUCTURAL/MECHANICAL
  - THERMAL/ENVIRONMENTAL
  - ELECTRICAL POWER
  - COMMUNICATIONS AND CONTROL/MONITOR

- INTERFACE MATRIX

<table>
<thead>
<tr>
<th></th>
<th>AIRCRAFT</th>
<th>TELESCOPE</th>
<th>CONSOLES/ ELECTRONICS</th>
<th>GROUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIRCRAFT</td>
<td>X</td>
<td>1</td>
<td>1 2</td>
<td>1 2 3</td>
</tr>
<tr>
<td>TELESCOPE</td>
<td></td>
<td>2</td>
<td>2 3 4</td>
<td>1</td>
</tr>
<tr>
<td>CONSOLES/ ELECTRONICS</td>
<td></td>
<td></td>
<td>X</td>
<td>4</td>
</tr>
<tr>
<td>GROUND</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
Control and Monitor Communications Interfaces
TOP-LEVEL COMMUNICATIONS INTERFACES
Summary and Conclusions

The goals of the SOFIA house phase A study have essentially been achieved, with the establishment of a solid foundation for future developments.
SUMMARY AND CONCLUSIONS

- BASIC FEASIBILITY ESTABLISHED
  - AIRCRAFT MODIFICATION - TECHNICAL AND COST
  - TELESCOPE SYSTEM - WITH MODERATE TECHNICAL RISK AREAS
  - OPERATIONS AND GROUND SUPPORT SYSTEMS - BASICALLY KAO UPGRADES

- COST ASSESSMENT
  - AIRCRAFT MODIFICATION
  - TELESCOPE SYSTEM
  - GROUND SUPPORT AND FACILITIES (C OF F)

- MAJOR RISK AREAS IDENTIFIED
  - TELESCOPE SYSTEM MASS
  - OPTICS PERFORMANCE AND TECHNOLOGY
  - POINTING PERFORMANCE
Assumptions:

Given the assumptions, the potential method would be to evaluate and verify K AO performance using similar models and configurations. The telescope and camera are the key elements of the system. The AO system consists of two main components: the AO corrector and the wavefront sensor. The AO corrector is responsible for correcting the wavefront errors, while the wavefront sensor measures the wavefront errors. The AO system is designed to work in real-time, correcting the wavefront errors as they occur.
ISSUES AND CONCERNS

- TELESCOPE SYSTEM
  - SYSTEM MASS (VS. STIFFNESS, DIMENSIONAL STABILITY, SIZE AND AIRCRAFT PERFORMANCE)
  - PRIMARY MIRROR POLISHING (VS. LARGER I/RATIO, RELAXED IMAGE QUALITY)
  - PRIMARY MIRROR MASS/AREAL DENSITY (VS. SIZE, STRUCTURE AND MOUNT DESIGNS)
  - STRUCTURAL/OPTICAL TOLERANCES FOR IMAGE QUALITY
  - AIR BEARING DESIGN AND MASS (NOT DEMONSTRATED)
  - POINTING STABILITY IN FLIGHT ENVIRONMENT (UNKNOWN LOADS)
  - CROSS ELEVATION/LOS ANGULAR RANGE (CAVITY VOLUME CONSTRAINT)
  - CAVITY/TELESCOPE THERMAL MODEL - VERIFICATION
This impacts the scope of effort required of NASA/ARC, the telescope contractor, and the aircraft modification contractor. Efforts have also been initiated in this area.

Finally, certain "project issues" have been identified requiring near-term review. First, a more comprehensive set of system requirements is needed for future program phases. With project, detailed and clear statement of system requirements is needed for future program phases. With project, detailed and clear statement of system requirements is needed for future program phases.

Issues and Concerns (cont)
ISSUES AND CONCERNS (CONTD)

- AIRCRAFT SYSTEM
  - INCREMENTAL DRAG (CLOSED DOOR AND DEPLOYED BLC FENCE, VS A/C PERFORMANCE)
  - ALLOWABLE BULKHEAD DEFLECTION (VS. MASS)
  - CAVALY "SEEING" AND SHEAR LAYER CONTROL DEVICES

- PROJECT ISSUES
  - DEVELOPMENT OF MORE COMPLETE AND DETAILED REQUIREMENTS
  - CONSIDERATION OF RELAXED REQUIREMENTS
  - DEFINITION OF SYSTEM/SUBSYSTEM BOUNDARIES, WORK ALLOCATION, AND RESPONSIBILITIES
SECTION 4

TELESCOPE SUBSYSTEMS DESCRIPTION

4.1 Optics
4.2 Telescope Structure
4.3 Air Bearing and Vibration Isolation System
4.4 Pointing and Control Subsystem
4.5 Data Management, Acquisition, and Communications
4.6 Telescope and Cavity Thermal Model
4.7 Instrument Accommodations
The focus locations accommodate scientific instruments at the Cassegrain focus, or at the Nasmyth focus on the instrument, may be accessed by personnel in the pressurized cabin.

The reconfigurable detector array is located in the instrument, in addition to having a high visible reflectivity and efficiency at a selected wavelength. It is also useful to specify image quality over an aperture in terms of projected image quality budget.
MAJOR OPTICAL REQUIREMENTS OF THE TELESCOPE

- PRIMARY MIRROR DIAMETER:  ≥ 2.5M (3.0M GOAL)
- SPECTRAL RANGE:  0.3µM < λ < 1600 µM
- CONFIGURATION:  GENERIC CASSEGRAIN, PROVISION FOR CASSEGRAIN OR NASMYTH FOCUS
- FIELD OF VIEW:  8 ARCMIN UNVIGNETTED
- SYSTEM F/RATIO:  
  F/11: CASSEGRAIN
  F/11-18: NASMYTH (ACCOMMODATED USING DIFFERENT SECONDARIES)
  F/13.5 & F/17: NASMYTH (STANDARD SECONDARIES)
- IMAGE QUALITY:
  VISIBLE: ≤ 1 ARCSEC DIA. ENCIRCLES 80% OF ENERGY IN IMAGE OF A POINT SOURCE ON AXIS AT 0.5 µM USING THE CENTRAL 2M APERTURE.
  ≤ 3 ARCSEC WITH 3M APERTURE
- PRIMARY MIRROR COATING:  BARE ALUMINUM
- FOCUS LOCATION:  
  CASSEGRAIN: 40 CM BEHIND THE PRIMARY MIRROR SUPPORT PLATE.
  NASMYTH: AFT OF THE AIR BEARING CENTERLINE.
  BETWEEN TELESCOPE AND AIR BEARING WITH SPECIAL FITTINGS
center and de-tell relative motions with limits prescribed by the system error budget.

The thermally induced changes in spacing between the primary and secondary mirror and keep de-

The secondary mirror is supported and balanced with special weightbell's. When balanced, the secondary mirror is supported and provides support to the secondary mirror. The secondary mechanism is supported in a housing by the slider which in turn attached to the

The telescope support ring and then to the spherical bearing by a

The telescope is attached to the telescope support ring and then to the spherical bearing by a

For submillimeter astrometry, the telescope focus shall be adjusted by large temperature changes, and to provide a "focuser drive" function to be employed. The mechanism will also make it possible to move the secondary aside to adjust the secondary mirror. The mechanism is mounted on a space-saving mechanism. The mechanism oscillates the

The secondary mirror is balanced to be no more than 1 kg, based on system performance and weight balance. The primary mirror baseline for this study will be of a weight, with weightless-type construction. Its

Building the secondary mirror would be removed or replaced with a beamsplitter if visible line focus is chosen. The secondary mirror to the Cassgrain focus, or the Nasmyth focus via the tertiary mirror. Depending on the choice of secondaries, that has been made. In the event the Cassgrain

The SOFA telescope is shown oriented vertically. Incoming light is focused toward the prime focus.
I
### COMA COEFFICIENTS FOR VARIOUS DESIGNS

<table>
<thead>
<tr>
<th>Design</th>
<th>paraboloidal</th>
<th>Ritchey-Chrétien</th>
<th>coma-compensated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prim mir conic cons</td>
<td>-1.000000</td>
<td>-1.000769</td>
<td>-1.001219</td>
</tr>
<tr>
<td>System focal ratio</td>
<td>13.5</td>
<td>17.0</td>
<td>13.5</td>
</tr>
<tr>
<td>Sec mir conic cons</td>
<td>-1.346</td>
<td>-1.266</td>
<td>-1.355</td>
</tr>
<tr>
<td>Field coma coeff</td>
<td>0.00103</td>
<td>0.00065</td>
<td>0.00038</td>
</tr>
<tr>
<td>Tilt coma coeff</td>
<td>0.09426</td>
<td>0.094071</td>
<td>0.09362</td>
</tr>
</tbody>
</table>

Conic constants are given in the system in which 0 represent a sphere and -1 a paraboloid.

Coma coefficients are ratio of point image angular size in astronomical space to field shift angle in astronomical space.
Primarily is as adequate as the Cassegrain. It would seem the coma-compensated Cassegrain should be rejected, and the slightly larger paraboloidal
designs. In this case the adantage of the Ritchey-Chretien begins to be seen.

do not necessarily choose the primary mirror and conic constant yet, but on the basis of present analysis
one of the field is brought into focus, were is possible to use a curved detector or additional optical

element to flatten the field. The field, in the Ritchey-Chretien and field coma would limit the field of view in these two
desigrs, in which a circle intermediate between the center point and the edge

doact a "best compromise focus", in which a circle intermediate between the center point and the edge
makes it difficult to bring the entire field to focus simultaneously on a flat detector. It is possible to
for the paraboloidal and equatorially designs the first limiting aberration is "nullification of field", which
consideration for SORFIA, field coma controls the field of view for the coma-compensated design.
The accompanying figure shows field-of-view as a function of wavelength for the designs under
consideration.

The accompanying figure shows field-of-view as a function of wavelength for the designs under
consideration.

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consideration.

The accompanying figure shows field-of-view as a function of wavelength for the designs under
consideration.

The accompanying figure shows field-of-view as a function of wavelength for the designs under
consideration.
UNIFORM QUALITY FIELD OF VIEW VERSUS WAVELENGTH

Field Diameter

arcmin

Ritchey-Chr'ien

Classical Cassegrain

Ritchey-Chr'ien or Classical Cassegrain

Coma-Compensated Cassegrain

Unvignetted Field

field is defined as area within which the image of a point source is no more than 20% larger than the best possible at the wavelength

Observation Wavelength

4-9

micron
available for the wavelength range to be used. This would in general depend on the instrument.

The compression of the expansion could be used to alter the focal ratio if a suitable form material is
(a) corrector focus will be the same role as prevented, and smaller (easter) than at the Nasmyth focus. In either case
(Cass矫正 focus will be more restricted, and smaller (easter) than at the Nasmyth focus. The role of the
may lead to restrictions on the focal ratios available at the Nasmyth focus. The role of the
telescope axis, and the slower the system, the further the focus from the prime. It is possible that when this
becomes a function of the system focal ratio in use. The faster the system the closer the focus to the
With the selection of a single size for the secondary mirror, the position of the Nasmyth system focus
optical beam to pass exactly through the center of the exit polar. This is somewhat different since there is no need for the
the same point, though the tertiary position could be somewhat different since there is no need for the
primary mirror of the telescope structure. The center of the tertiary mirror is conventionally placed at
namely the top of the secondary mirror mechanism and the outermost edges, just below the base of the
be at the center of a circle which is tangent to the tertiary points of the telescope, which is tangent to the
for geometric and considerations, the point of the system focal ratio. Parallel to the long axes of the
be at the center of a circle which is tangent to the tertiary points of the telescope, which is tangent to the
The rotation of the telescope to different elevations determines the focus. The rotation of the
aperture below the primary mirror clear aperture.

view and regardless of the within the spectrometer limit. This will also reduce the system aperture
Guaranteed in functions as the spectrometer aperture stops at all points within the desired unobstructed field of
primary mirror to the prime focus. In the first design it will be moved slightly closer, so as to
the secondary mirror is positioned with respect to the primary mirror so as to fill the cone from the
The secondary mirror is surrounded by the secondary mirror clear aperture. We have used 300m as the allowed secondary mirror clear
structure surrounding the secondary mirror. The secondary mirror mechanism, although the length of the secondary
in particular, assumptions have been make concerning the length of telescopes will fill in the majority. In particular, assumptions have been make concerning the length of
the fifteen or thirty meters. Instead of a length estimate of a given aperture and a given focal length, have been
assumed. It has been verified that under reasonable estimates of other aberrations and some mechanical tolerances. It has not been possible to make possible determinations
of observational efficiency, and for the primary mirror focal length to be as large as possible to increase
with these conditions is desirable for the primary mirror to be as large as possible, to increase

chip if.

An additional constraint is the limit on the size of the secondary mirror placed by the need to
The layout of the SOFI telescope is most strongly constrained by the need to fit within the
Eliminate Jougalt
System focal ratios: The secondary mirror and its support structure will be removable and replaceable. This will allow observation at varying focal ratios. Two secondary mirrors will be supplied, one for operation at f/1.5 and one at f/1.7. The system will be capable of accomodating focal ratios from f/1.1 to f/18.

Function of the secondary mirror in use: The field of view and chopping with the aperture stop at the secondary mirror. The exact value is a matter of design and geometry of the system. The useful astronomical aperture will be slightly less than this, to allow for the unvignetted diameter. The useful astronomical aperture will be slightly less than this, to allow for the unvignetted diameter.

Primary Mirror: SOFIA is planned to have a primary mirror with up to a three meter usable point. Direction (e.g. "for scans").

Secondary Mirror: The secondary mirror will be articulated. This will allow "chopping" observation, in which the instrument alternately sees the target and blank sky, and fine adjustment of the effective aperture. This will allow introduction of the effective aperture. This will allow introduction of the effective aperture.

Active Secondary: Because the telescope will not be cryogenically cooled, it will "flaw" at infrared degree angles. Because the telescope will not be cryogenically cooled, it will "flaw" at infrared degree angles. It is sometimes referred to as "undercutting the secondary." A flats mirror in addition to the secondary mirror. This is sometimes referred to as "undercutting the secondary.

The system will include a tertiary mirror placed between the primary and secondary mirrors at a 90 degree angle. It is a removable, flat, tertiary mirror that will be replaceable with a tertiary mirror placed between the primary and secondary mirrors. This will mean that the system will be capable of accommodation.

Optical Precaution:
# SOFIA OPTICAL PRESCRIPTION

<table>
<thead>
<tr>
<th>Element</th>
<th>Separation</th>
<th>Diameter</th>
<th>Quality</th>
<th>Focal Length</th>
<th>Conic Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f/13.5</td>
<td>f/17</td>
<td></td>
<td>f/13.5</td>
<td>f/13.5</td>
</tr>
<tr>
<td>Primary mirror</td>
<td>3000mm - 300mm</td>
<td>0.6urms</td>
<td>3000mm</td>
<td>-1.0000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2700mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary mirror</td>
<td>300mm - 22mm</td>
<td>0.3urms</td>
<td>324mm</td>
<td>319mm</td>
<td>-1.3456</td>
</tr>
<tr>
<td></td>
<td>1780mm</td>
<td></td>
<td></td>
<td></td>
<td>-1.2656</td>
</tr>
<tr>
<td>Tertiary mirror</td>
<td>300mm x 400mm</td>
<td>0.3urms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2270mm</td>
<td>3320mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Focal plane</td>
<td>120mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

"Diameters" are outer and inner for primary and secondary, minor and major for tertiary.
Telescope Wavelength Error Budget - 2 m Aperture

The SOFIA telescope wavelength error (WMF) budget is based on the image quality requirements of a strategic telescope with no spectroscopic capabilities, and on the need for the highest image quality achievable. The wavelength error, which would encroach on the field of view, is determined by the need for the central 2-meter diameter portion of the field of view. This portion is equivalent to a 1-to-1 mirror, for which the point of observation is encircled by a 2-meter diameter portion of the field of view. The requirement is that encircled by a 2-meter diameter portion of the field of view. For specification and analysis purposes, requirements were established for the seeing conditions.

The image quality requirements were established for the seeing conditions and are a function of the telescope's aperture and distance to the target. The shortest operating wavelength at the center of the field, with the secondary illuminated, is discussed in addition to the telescope's ability to be characterized by its best achievable qualities. The secondary illuminated, when the secondaries are completely illuminated, is discussed in addition to the telescope's ability to be characterized by its best achievable qualities. The secondary illuminated, when the secondaries are completely illuminated, is discussed in addition to the telescope's ability to be characterized by its best achievable qualities. The secondary illuminated, when the secondaries are completely illuminated, is discussed in addition to the telescope's ability to be characterized by its best achievable qualities. The secondary illuminated, when the secondaries are completely illuminated, is discussed in addition to the telescope's ability to be characterized by its best achievable qualities.
TELESCOPE WAVEFRONT ERROR BUDGET - 2 M APERTURE

TELESCOPE 0.53 μm

OPTICS 0.40 μm

PRI. MIRROR 0.24 μm

SEC. MIRROR 0.19 μm

TER. MIRROR 0.15 μm

WINDOW 0.20 μm

FABRICATION 0.15 μm

FABRICATION 0.10 μm

FABRICATION 0.10 μm

FABRICATION 0.16 μm

METROLOGY 0.06 μm

METROLOGY 0.06 μm

METROLOGY 0.06 μm

METROLOGY 0.06 μm

MOUNT 0.10 μm

MOUNT 0.10 μm

MOUNT 0.10 μm

MOUNT 0.10 μm

DISTORTION 0.10 μm

ASTIGM. 0.10 μm

ASTIGM. 0.10 μm

DESSPACE 0.13 μm

PRI. DISTOR. 0.21 μm

SEC. DISTOR. 0.09 μm

TER. DISTOR. 0.09 μm

TER. POSITION 0.03 μm

FOCUS INCRE. 0.06 μm

FOCUS JUDGE. 0.11 μv

FOCUS 0.31 μm

ALIGNMENT 0.17 μm

DECENTER 0.09 μm

TILT 0.15 μm

λν = 0.633 MICRON
λD. L. = 14 × RMS WFE
= 7.4 MICRONS
that the wavefront allocations for the two apertures are the same.

As one might expect, the primary mirror, mount and other mounts are the same for both apertures, so

"Effects on the P1 Primary Mirror." The difference in wavefront error, according to the tolerances on the primary mirror, mount and other mounts, is negligible. Therefore, the wavefront errors resulting from each of the mirrors may be considered to the performance criteria. The difference in the wavefront errors at each mirror is negligible. Therefore, the wavefront errors may be considered to the performance criteria.

The difference in the wavefront errors at each mirror is negligible. Therefore, the wavefront errors may be considered to the performance criteria.

Telescope Wavefront Error Budget - $m$ Aperture
of the telescope. Tolerances in these columns will usually result from non-photical considerations.

that any error can be accepted, but only that an error does not immediately reduce the imaging ability
combined Jill is greater than in the column to the left, the presence of an "exposure" tolerance does not mean
when there is no tolerance in a column, those effects are to be considered part of the effects whose

The accompanying table presents tolerances for the SOFI telescope based on the optimal requirements.
# SOFIA Optical Tolerances

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Absolute</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary mirror focal length</td>
<td>3000 mm</td>
<td>0.008 mm</td>
<td>0.005 mm</td>
</tr>
<tr>
<td>Primary mirror central sag</td>
<td>188 mm</td>
<td>.000127 mm</td>
<td>.00005 mm</td>
</tr>
<tr>
<td>Primary mirror surface error</td>
<td>.000063 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central area surface error</td>
<td>.00063 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary mirror distortion</td>
<td>.00075 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary mirror tilt vector</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary mirror focal length</td>
<td>320 mm</td>
<td>.002 mm</td>
<td>.001 mm</td>
</tr>
<tr>
<td>Secondary mirror central sag</td>
<td>17 mm</td>
<td>.00015 mm</td>
<td>.00001 mm</td>
</tr>
<tr>
<td>Secondary mirror surface error</td>
<td>.000033 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary mirror distortion</td>
<td>.05 mm</td>
<td>.001 mm</td>
<td>.001 mm</td>
</tr>
<tr>
<td>Secondary versus primary decenter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary mirror tilt vector</td>
<td>60 arcsec</td>
<td>.5 arcsec</td>
<td></td>
</tr>
<tr>
<td>Distance from primary to secondary</td>
<td>2700 mm</td>
<td>.005 mm</td>
<td></td>
</tr>
<tr>
<td>Tertiary mirror central sag</td>
<td>0</td>
<td>.0001 mm</td>
<td></td>
</tr>
<tr>
<td>Tertiary mirror surface error</td>
<td>.000033 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tertiary mirror distortion</td>
<td>.00015 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance from primary to tertiary</td>
<td>920 mm</td>
<td>.2 mm</td>
<td>.01 mm</td>
</tr>
<tr>
<td>Tertiary mirror tilt vector</td>
<td>45 degree</td>
<td>.5 arcsec</td>
<td>.5 arcsec</td>
</tr>
<tr>
<td>Distance from axis to instrument</td>
<td></td>
<td>.5 mm</td>
<td>.02 mm</td>
</tr>
<tr>
<td>Instrument misposition vector</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Jitter | .05 arcsec | |
Drift between focusing operations, plus any vibrational motion.
The drift tolerance is the allowable change in the distance between the mirrors at their centers of focus. "Drift" means change in the distance by planes tangent to the surfaces of the two mirrors as determined by interfered wavefronts beyond about 12 microns. The full unvignetted field will be of comparable quality. The edge of the field will be about 10 percent larger than at the center, at visible wavefronts. If the third-order optical design is either parabolic or elliptic, then the image diameter at the field for the required image quality and unvignetted field of view will be the largest diameter at the image quality limits.

There are two undesirable side-effects of such a fast primary. They are a reduced quality field of view and drift tolerance on the positioning of the secondary mirror with respect to the primary.

Effects of the 7/1 Primary Mirror.
Additional concerns include long-term stability, a suitable surface for polishing, and suitable metric smoothness. Additional concerns include long-term stability, a suitable surface for polishing, and suitable metric smoothness. Additional concerns include long-term stability, a suitable surface for polishing, and suitable metric smoothness. Additional concerns include long-term stability, a suitable surface for polishing, and suitable metric smoothness. Additional concerns include long-term stability, a suitable surface for polishing, and suitable metric smoothness. Additional concerns include long-term stability, a suitable surface for polishing, and suitable metric smoothness. Additional concerns include long-term stability, a suitable surface for polishing, and suitable metric smoothness. Additional concerns include long-term stability, a suitable surface for polishing, and suitable metric smoothness. 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Additional concerns include long-term stability, a suitable surface for polishing, and suitable metric smoothness.
CANDIDATE PRIMARY MIRROR TECHNOLOGY

+ = HST
Δ = Cast (ground-based)
Δ = Cast (SOFIA estimate)
○ = Advanced HST
△ = Frit Bonded
□ = Zerodur Meniscus (thickness in mm)

PRIMARY MIRROR WEIGHT (KG)

MAXIMUM TELESCOPE APERTURE (METERS)

125 kg/m2
100 kg/m2
50 kg/m2

Desired Space for SOFIA
of a large mirror made of this material. Consequently the whole system, much needs to be done to determine the expected optical performance.

Near the lower west area density shown is an estimate provided by MAN for the Carbon Fiber Reinforced Plastic (CFRP) technology. It has great promise for reducing the weight of the telescope and blisks. The estimates were prepared in collaboration with the MAN study.

Also shown are two estimates prepared by the Stewart Mirror Laboratory for spin-cast borosilicate glasses. The estimates were prepared by the Stewart Mirror Laboratory for spin-cast borosilicate glasses, and are representative of solid, thin mirror mirrors made of short Zerodur at constant thicknesses of 40 mm and 50 mm. Studies by Zeiss of the membranes indicate that this technology is a viable candidate.

The Prominent Heavy Line connects the two size and weight estimates provided by Klock for MAN, for the Carbon Fiber Reinforced Plastic technology. The top two of the lines are resilient at 100 Kgf/m, respectively. This technology is well within the desired range.

Given technology it will be governed by lack of mirror stiffness. This study did not explore a lower limit. Nevertheless, this study has been intelligently directed in order to consider the expected weight and performance. In particular, the upper weight boundary is defined as about 3 m has been intelligently directed. The upper weight boundary is defined as about 3 m has been intelligently directed. The upper weight boundary is defined as about 3 m has been intelligently directed. The upper weight boundary is defined as about 3 m has been intelligently directed.
SOFIA PRIMARY MIRROR SIZE/WEIGHT TRADEOFF

PRIMARY MIRROR WEIGHT
(KG) (LBS)
800 1600
700 1500
600 1400
500 1300
400 1200
300 1100
200 1000
100 900
0 800

MAXIMUM TELESCOPE APERTURE (METERS)
2.4 2.5 2.6 2.7 2.8 2.9 3.0

OBSERVATION TIME PENALTY

ZEISS MENISCUS
125 KG/M2
100 KG/M2

CORNING FRIT BONDED
90 KG/M2
36 MM

MAN CFRP
60 KG/M2

STEWARD CAST
40 MM

50 MM

TOO LARGE FOR 747

APERTURE TOO SMALL
Thorough efforts are being made to develop carbon fiber-reinforced-plastic (CFRP) mirror blanks for the 15-m diameter SOFIA telescope, which is designed for its inherent stability. This form is necessary for the inherent stability of the telescope system. Technology is reported to be 1.5 m in diameter and a real density of 1.72 g/cm².

Design problems for suitable mounting both on polishing and for flight are encountered by existing thinner face sheets and this.

Recent efforts at the Steward Observatory Laboratory for arc erosion sample mirror blanks of 10 mm thick, 117 mm in diameter, with a 12-mm-thick dorso-silica mirror. The design problem is that the current VATT or ARC blank can take the spin-p coating technology even beyond the SOFIA size, but a higher area density.

Recently, efforts at the Steward Observatory Laboratory for arc erosion sample mirror blanks of 10 mm thick, 117 mm in diameter, with a 12-mm-thick dorso-silica mirror. The design problem is that the current VATT or ARC blank can take the spin-p coating technology even beyond the SOFIA size, but a higher area density.
# Lightweight Primary Mirror Blank Technology for SOFIA

<table>
<thead>
<tr>
<th>Areal Density (kg/m²)</th>
<th>Application</th>
<th>Type</th>
<th>Dia. (m)</th>
<th>Material</th>
<th>F/Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accomplished:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>184</td>
<td>HST</td>
<td>FUSED</td>
<td>2.4</td>
<td>ULE</td>
<td>2.3</td>
</tr>
<tr>
<td>252</td>
<td>VATT¹</td>
<td>SPIN-CAST</td>
<td>1.8</td>
<td>OHARA E6</td>
<td>1.0</td>
</tr>
<tr>
<td>23</td>
<td>DEVEL.</td>
<td>FRIT</td>
<td>0.5</td>
<td>FUSED SILICA</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Scheduled:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>197</td>
<td>ARC²</td>
<td>SPIN-CAST</td>
<td>3.5</td>
<td>OHARA E6</td>
<td>1.75</td>
</tr>
<tr>
<td>32</td>
<td>DEVEL.</td>
<td>FRIT</td>
<td>1.5</td>
<td>ULE</td>
<td>?</td>
</tr>
<tr>
<td><strong>Studied:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>165</td>
<td>SOFIA³</td>
<td>SPIN-CAST</td>
<td>3.5</td>
<td>OHARA E6</td>
<td>1.0</td>
</tr>
<tr>
<td>127</td>
<td>SOFIA⁴</td>
<td>MENISCUS</td>
<td>2.8</td>
<td>ZERODUR</td>
<td>1.0</td>
</tr>
<tr>
<td>110</td>
<td>SOFIA⁵</td>
<td>FRIT</td>
<td>2.9</td>
<td>ULE</td>
<td>1.0</td>
</tr>
<tr>
<td>103</td>
<td>SOFIA⁶</td>
<td>CAST</td>
<td>2.9</td>
<td>OHARA E6</td>
<td>1.0</td>
</tr>
<tr>
<td>60</td>
<td>SOFIA⁷</td>
<td>COMPOSITE</td>
<td>2.9</td>
<td>CFRP</td>
<td>1.0</td>
</tr>
</tbody>
</table>

1 VATT = VATICAN ADVANCED TECHNOLOGY TELESCOPE, PRESENTLY FUNDED
2 ARC = ASTROPHYSICAL RESEARCH CORP. (U. CHICAGO, PRINCETON U., U. WASHINGTON, U. NEW MEXICO)
   TO BE CAST IN SPRING 88, LOCATION - APACHE POINT, NEW MEXICO.
3 ESTIMATE FROM STEWARD OBSERVATORY LETTER OF 7/5/85
4 ZEISS STUDY MIDTERM ESTIMATE, THICKNESS = 50 MM
5 ESTIMATE FROM CORNING
6 STEWARD OBSERVATORY "REASONABLE GOAL" ESTIMATE, MAN STUDY FINAL REPORT
7 MAN STUDY FINAL REPORT
A concept invented by Zelis is called the membrane lapping. This concept calls for a flexible membrane to be placed on the mirror to be lapped. A membrane made of stretched rubber is effective in lapping a mirror. The membrane is placed on the mirror, and the lapping tool is moved over the mirror. The tool is then removed, and the mirror is washed to remove the membrane. This technique is effective in lapping a mirror without removing the surface of the mirror.

Another solution to the low lapping efficiency problem is the use of a computer-controlled lapping machine. This machine can be used to lapping a mirror, and the lapping tool can be moved over the mirror. The lapping tool is moved over the mirror, and the lapping machine is moved to the next position to continue the lapping process. This technique is effective in lapping a mirror, and the lapping efficiency is improved.

In conclusion, the concept of using a computer-controlled lapping machine is effective in lapping a mirror. The lapping efficiency is improved, and the mirror can be lapped without removing the surface of the mirror.
## FINISHING TECHNOLOGY FOR LOW F/RATIO PRIMARY MIRRORS

<table>
<thead>
<tr>
<th>POLISHING METHOD</th>
<th>F/RATIO</th>
<th>DIA. (M)</th>
<th>TYPE</th>
<th>MATERIAL</th>
<th>STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>FULL LAP</td>
<td>0.8</td>
<td>1.2</td>
<td>FUSED</td>
<td>ULE</td>
<td>COMPLETE&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>STRESSED LAP</td>
<td>1.0</td>
<td>1.8</td>
<td>SPIN-CAST</td>
<td>OHARA E6</td>
<td>FUNDED</td>
</tr>
<tr>
<td>MEMBRANE LAP</td>
<td>1.0</td>
<td>2.8</td>
<td>MENISCUS</td>
<td>ZERODUR</td>
<td>DEVELOPMENTAL</td>
</tr>
<tr>
<td>SUB-DIAMETER LAP&lt;sup&gt;2&lt;/sup&gt;</td>
<td>1.75</td>
<td>3.5</td>
<td>SPIN-CAST</td>
<td>BOROSIL</td>
<td>PLANNED&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>SMALL LAP&lt;sup&gt;4&lt;/sup&gt;</td>
<td>2.3</td>
<td>2.4</td>
<td>FUSED</td>
<td>ULE</td>
<td>COMPLETE</td>
</tr>
<tr>
<td>FULL LAP&lt;sup&gt;5&lt;/sup&gt;</td>
<td>2.3</td>
<td>2.4</td>
<td>FUSED</td>
<td>ULE</td>
<td>COMPLETE</td>
</tr>
</tbody>
</table>

<sup>1</sup> DEPT. OF DEFENSE FUNDED DEMO (NO EXPORT TECHNOLOGY RESTRICTION)

<sup>2</sup> POLISHING BY NORM COLE, TUCSON

<sup>3</sup> WILL BE THE FIRST 3.5 M, SPIN-CAST PRIMARY

<sup>4</sup> COMPUTER CONTROLLED POLISHER; HST FLIGHT UNIT - PERKIN ELMER CORP.

<sup>5</sup> FULL DIAMETER LAP; HST ALTERNATE - EASTMAN KODAK

---

4 - 29
The mechanical tolerances associated with an f/1 primary mirror will lead to some stringent error terms, and with an allowance of only 1 micrometer change in mirror spacing during the time an observation is made, it is clear that a nulling interferometer can be increased in thickness quite easily if desired.

The strength of a lightweight glass mirror is a concern in that the desire to reduce weight tends to reduce surface roughness.

It is not yet known what the sensitivity of high spatial frequency surface errors in the primary mirror would be.

Concerns and Risks
CONCERNS AND RISKS

- FABRICATION OF THE LARGE, LIGHTWEIGHT PRIMARY MIRROR BLANK
  - RISK: COST, SCHEDULE GROWTH
  - RISK REDUCTION: EARLY DESIGN STUDIES, TECHNOLOGY DEVELOPMENT, CONSIDER USING ALTERNATIVE TECHNOLOGY

- FINISHING OF THE F/1 PRIMARY MIRROR
  - RISK: COST, SCHEDULE GROWTH
  - RISK REDUCTION: TECHNOLOGY DEVELOPMENT, REDUCE IMAGING REQUIREMENTS

- STRENGTH OF PRIMARY MIRROR
  - RISK: MIRROR FRACTURE
  - RISK REDUCTION: INCREASE WEIGHT/REDUCE APERTURE - MARGIN EXISTS BELOW 3M TO MEET 680 KG (1500 LB) OBJECTIVE

- HIGH SPATIAL FREQUENCY, PRIMARY MIRROR SURFACE ERRORS
  - RISK: COST OF ADDITIONAL ANALYSIS AND DESIGN
  - RISK REDUCTION: EARLY DESIGN STUDIES, ADDITIONAL MOUNT CAPABILITY

- MECHANICAL TOLERANCES ASSOCIATED WITH THE F/1 PRIMARY MIRROR
  - RISK: FOCUS, IMAGE QUALITY VARY WITH TEMPERATURE, ELEVATION
  - RISK REDUCTION: DESIGN STUDIES, REDUCE APERTURE AND MIRROR F/RATIO

- LOW INERTIA SECONDARY MIRROR FOR CHOPPER
  - RISK: LESS DYNAMIC PERFORMANCE OF THE CHOPPER
  - RISK REDUCTION: TECHNOLOGY DEVELOPMENT
decisions are made. A selection of these have been studied in more detail, results being presented in other sections of this report. It does appear that all of the tolerances can be met, provided proper design and image filter etch or budgets have been developed from which meaningful Waverton, focus, and image filter etch or budgets have been developed from which meaningful
The primary mirror should preferably have a paraboloidal figure. Either this, or a slightly hyperboloidal figure.
which has the maximum aperture geometrically allowed.
concepts has difficulties, it appears they are not insurmountable. Thus a telescope design is feasible.
The rest and highly curved f/1 primary is called for off the telescope within the concrete, while this
intersection of secondary mirrors. Two secondary mirrors will be supplied designed for f/13,5 and f/17.
The SOFIA telescope will be a Cassegrain/Nasmyth, it will have a primary mirror of 2.5 to 3 meters
Optics Summary

and finishing remain extremely important areas worthy of study and technology development. First, the weight primary mirror blank, and in the finishing of the mirror. Nevertheless, replication
A number of technologies have been identified that can be employed in the replication of the large,
SELECTED CONCEPTS AND ALTERNATIVES

- CASSEGRAIN TELESCOPE WITH TERTIARY FLAT FOR NASMYTH FOCUS
- CLASSICAL CASSEGRAIN OPTICAL DESIGN
  - ALTERNATIVE: RITCHEY-CHRETIEN
- FRIT-BONDED ULE PRIMARY MIRROR
  - ALTERNATIVES: THIN MENISCUS OF ZERODUR, CAST BOROSILICATE
- TELESCOPE METERING STRUCTURE
  - ALTERNATIVE: MORE FREquent REFOCUS AND ALIGNMENT
- LOW-INERTIA SECONDARY FOR CHOPPING
  - ALTERNATIVE: HIGHER INERTIA, REDUCED CHOPPING PERFORMANCE
Requirements will have to be developed in future project phases. More detailed specifications for the chopper performance and configuration investigation are needed. The requirement is to provide in-flight focusing capability, both to retrace the telescope for functional requirement and to provide a high-resolution assembly to determine if the design is required. A functionally needed of the chopper/selector/mechanism assembly is a high-resolution, dynamic assembly that requires more power (the actuators must deflect both masses, further structural dynamic analysis is required). The mirror requires a high-performance, high-resolution design to meet these needs.

The mirror will be made of a molybdenum, mirror material of choice. The mirror material must be high-performance, high-resolution design to meet these needs. The secondary mirror/exit pupil is expected to have an 80 cm diameter, with -2.5 cm thickneses needed for the secondary mirror/exit pupil.
SECONDARY MIRROR CHOPPER SUBSYSTEM
REQUIREMENTS SUMMARY

<table>
<thead>
<tr>
<th>CHOP AMPLITUDES</th>
<th>0.17 MIN</th>
<th>5</th>
<th>20</th>
<th>40 MAX</th>
<th>(ARC MIN, P-P; MIRROR THROW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRANSITION TIME</td>
<td>NO SPEC</td>
<td>≤5</td>
<td>≤7</td>
<td>NO SPEC</td>
<td>(mSEC, SQUARE WAVE)</td>
</tr>
<tr>
<td>FREQUENCIES</td>
<td>NO SPEC</td>
<td>1-35</td>
<td>1-10</td>
<td>NO SPEC</td>
<td>(Hz, INTEGER VALUES ONLY)</td>
</tr>
<tr>
<td>END POSITION STABILITY</td>
<td></td>
<td>≤ 1% OF CHOP AMPLITUDE</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MIRROR PROPERTIES

| MATERIAL: LOW EXPANSION GLASS OR GLASS CERAMIC |
| DIAMETER: ~ 30.5 CM | THICKNESS: ~ 2.5 CM (DERIVED) |

CHOPPER CONFIGURATION

| DUAL AXIS ACTUATING; REACTIONLESS (IF NECESSARY) |
| ENVELOPE: 30.5 CM DIA X 35.5 CM LENGTH |

FUNCTIONS

| CHOP: SQUARE WAVE, SAWTOOTH, "ARBITRARY," SCAN; OFFSET CHOP |
| FOCUS: ADJUSTABLE, DITHER (AMPL.: 0.05 TO 0.5 MM; FREQUENCY: 5 TO 25 Hz) |
Theoretically, the armature penalty (pan) will minimize the average power losses due to resistance in the armature circuit. Pulse widths of 33% of the transition time will not predict as low a torque as for 50%, but will predict higher. Because it is a good, conservative approximation, it is often used as a basis for regulating requirements. A sine wave is a very reasonable approximation also, but amplifiers which incorporate current feedback schemes very close, assuming the motor inductance is low enough so as not to require huge voltages. A sine wave is a very reasonable approximation also, but amplifiers which incorporate current feedback schemes very close, assuming the motor inductance is low enough so as not to require huge voltages. Although it is impossible to produce perfect pulses, a high-bandwidth current regulator, reasonable models are based on torque pulses which can actually be produced by state-of-the-art amplifiers.

In order to calculate the torque required to excite the chopper, a model of the transition profile is necessary.
IDEALIZED CHOPPER TRANSITION PROFILES

**DERIVED FROM PULSE ACCELERATIONS**

\[ \theta_0 = \frac{A}{2a(t-a)} \left( \frac{t}{t_r} \right)^2 \]

\[ \theta_1 = \frac{A}{l - a} \left( \frac{t}{t_r} \right) \]

\[ \theta_2 = A \left[ 1 - \frac{1}{2a(t-a)} \left( 1 - \frac{t}{t_r} \right)^2 \right] \]

\[ \theta_3 = \frac{A}{a(t-a)} \left( \frac{t}{t_r} \right) \]

\[ \theta_4 = \frac{A}{a(t-a)} \left( \frac{t}{t_r} \right) \left( 1 - \frac{t}{t_r} \right) \]

\[ \theta_5 = \frac{A}{a(t-a)} \left( \frac{t}{t_r} \right) \]

\[ \theta_6 = 0 \]

\[ \theta_7 = -\frac{A}{a(t-a)} \left( \frac{t}{t_r} \right)^2 \]

**DERIVED FROM SINE ACCELERATIONS**

\[ \phi = \frac{A t}{t_r} - \frac{A}{2 \pi} \sin \left[ \frac{2 \pi t}{t_r} \right] \]

\[ \dot{\phi} = \frac{A}{t_r} \left[ 1 - \cos \left[ \frac{2 \pi t}{t_r} \right] \right] \]

\[ \ddot{\phi} = \frac{A 2 \pi}{t_r^2} \sin \left[ \frac{2 \pi t}{t_r} \right] \]
considered before choosing the actuators. A small additional spring torque should be
required. Actuators in this range are readily available. To meet the 20 arcmin at 7
N per actuator requirement, 57 N per actuator are called for. For an actuator
amplitude, two actuators which can produce 28 N each will be required for
of 1 m and a 5 arcmin amplitude. In terms of actuator, assuming an actuation radius
will be required to translate 15 m. In terms of angle the actuator, assuming a
torque can be made with a moment of inertia (M0) of 0.15 kg-m². A torque of about 1.1
N-m/arcmin was calculated using the transition profile formulas on the previous sheet. Assuming a
Inertial Torque
REQUIRED INERTIAL TORQUES

TORQUE FUNCTION

- SINE
- PULSE

\( t_s (\text{msec}) \)

\[ \text{N-m ARChV} \]

\[ \text{TORQUE AMPLITUDE} \]

\[ \text{MOI - J Kg-m}^2 \]

\( \alpha = 0.33 \)
To reduce the mirror moment of inertia to as low a value as possible, it is important to machine away as much material near the perimeter of the mirror as is practicable. Based on a combination of tapering and open-back machining, it is possible to reduce the MOI to 60% of its original value.

Although a complete structural analysis should be performed to ensure that the mirror has not been weakened excessively, starting with a 4 kg blank of fused silica, one should be able to get a MOI of about 0.15 Kg mm².
MOI REDUCTION

\[
\frac{I'_{xx}}{I_{xx}} = \frac{2(4b/a + 1)}{x}
\]

\[
\frac{I'_{xx}}{I_{xx}} = 1 - \frac{c}{a}[(r_2/R)^4 - (r_1/R)^4]
\]

<table>
<thead>
<tr>
<th>TAPERING</th>
<th>OPEN-BACK MACHINING</th>
</tr>
</thead>
<tbody>
<tr>
<td>b/a</td>
<td>I'<em>{xx}/I</em>{xx}</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>3/4</td>
<td>.80</td>
</tr>
<tr>
<td>1/2</td>
<td>.60</td>
</tr>
<tr>
<td>0</td>
<td>.20</td>
</tr>
<tr>
<td>1/4</td>
<td>.40</td>
</tr>
<tr>
<td>1</td>
<td>1.0</td>
</tr>
</tbody>
</table>

4-41
higher bandwidth to achieve the same settling time. Notice that bandwidth is a function of damping ratio. Lower damping ratios will require wider bandwidth at a damping ratio of 0.7. This is consistent with bandwidth quoted for similar systems. To meet SOPTA specifications a 5 μsec transition time with 1% error in the final value is a bandwidth goal value within a defined error. Better suited for defining chopping performance since it is the time required for the step to reach the response is a suitable method of determining bandwidth available to produce the desired chopping response. An advantage of a classical second-order step response is that the control system bandwidth must be chosen carefully to ensure that enough harmonic content is present. Chopper Bandwidth Selection.
moderately stiff and compliant motor-mirror junction with 0.5 damping, reflecting a possible SOPIA chopper configuration were chosen and results were generated for both a

The motor, a simple component, is used to achieve the desired bandwidth of 725 Hz. Parameters of the motor, position and velocity feedback are incorporated. However, a performance

A simple chopper dynamic model was analyzed to understand more fully the effect that unwanted resonances might have on the control system. A simple control system model was used to study the

Any structural resonances should be 5 times higher than the desired system bandwidth. To avoid any structural resonances that will cause problems with controlling the mirror,traditionally,

From a survey of various existing chopper mechanisms, one point of general agreement is that the stiffness...
STIFFNESS OF CHOPPER MECHANISM

CHOPPER MODEL

FIXED PARAMETERS

\[ M_m = 4.1 \text{ Kg} \]
\[ M_a = .37 \text{ Kg} \]
\[ J = .015 \text{ Kg-m}^2 \]
\[ R = .10 \text{ m} \]
\[ \zeta = .05 \]
\[ \omega_m = 94 \text{ sec}^{-1} \]
\[ B_2 = 2\omega_m J = .14 \text{ N-m-s} \]
\[ K_2 = \omega_m^2 J = 132 \text{ N-m} \]

Mirror Mass
Actuator Core Mass
Mirror MOI
Actuation Radius
Damping Ratio
Mirror Resonance
Mirror Damping
Mirror Stiffness

VARIABLE PARAMETERS

Moderately stiff \( f_a = 1590 \text{ Hz} \)
\[ \omega_a = 10,000 \text{ sec}^{-1} \]
\[ B_1 = 370 \text{ Kg-sec}^{-1} \]
\[ K_1 = 3.7 \times 10^7 \text{ Kg-sec}^{-2} \]

Compliant flexure \( f_a = 500 \text{ Hz} \)
\[ \omega_a = 3,142 \text{ sec}^{-1} \]
\[ B_1 = 116 \text{ Kg-sec}^{-1} \]
\[ K_1 = 3.7 \times 10^6 \text{ Kg-sec}^{-2} \]
Feedback is key in the velocity of the mirror instead of the mirror as shown in the following example.

The best solution is to ensure that all resonant frequencies are either high or well damped and to

Peak Observer/Chopper system.

the only other compensation option is to introduce a notch filter at the resonant frequency. This will

the desired performance under these circumstances.

achieve the required bandwidth (the case as shown), the

7. If the position gain is increased in an attempt to achieve the bandwidth at the required damping ratio of

frequency so that the eigenvalues are for two actuators as if they were tied together.

Figure 7.1 shows the desired bandwidth of 225 Hz. This value is a little higher than the one calculated for the resonant

A resonance near 1900 Hz is apparent from looking at the Bode diagram - a factor of 8.4 higher than

(velocity feedback at mirror)

Chopper Mechanism - Modulated Signal System
STIFFNESS IN CHOPPER MECHANISM
MODERATELY STIFF SYSTEM

Velocity and Position Sensors
Mounted on Mirror

4-47
Therefore, by simply taking the velocity feedback from the motor rather than from the mirror, the performance of the position loop so as to meet the required specifications.

At resonance at 1900 Hz, if the problem is present, no major problem to the control system.

In turn, it is possible to get exceptional system to achieve high bandwidth in the velocity loop. In turn, it is now becomes possible to introduce enough velocity feedback into the axis, when the gain K_v is increased. If not, it becomes possible to introduce enough velocity feedback into the system, in that the poles are no longer drawn across the imaginary introducing a notch filter into the system, in that the poles are no longer drawn across the imaginary.
STIFFNESS IN CHOPPER MECHANISM
MODERATELY STIFF SYSTEM

Velocity Sensor on Motor
Position Sensor on Mirror
In reducing the burden on the control system, the use of velocity and torque feedback would have been demonstrated successfully. By others

A velocity feedback at the motor, a more practical controller would be designed to follow a trajectory trajectory or path. This would then be presented to be a final design, but only to suggest the use of

The control issues shown here are not intended to be a final design but only to suggest the use of

a notch filter so as to arrive at a robust control design.

If velocity sensing had not been used, a similar response could have been simulated using a more

The velocity loop, an excellent response can still be obtained.

(velocity feedback at motor)

Chopper Mechanism - Compliant System
misalignments and deceleration of the helicopter mounting location. A NASTRAN structural model will provide the transfer function to compute angular shown. A NASTRAN structural model will provide the transfer function to compute angular

A torque forcing function was generated to investigate the dynamic response of the telescope slider support structure and give a basis for deciding the need for a reactionless chopper system. The first

Structural Evaluation
STRUCTURAL EXCITATION
Harmonic Content of Chopper
Unity Torque Function (80% Duty Cycle)
First 19 Modes

<table>
<thead>
<tr>
<th>n</th>
<th>a_n</th>
<th>b_n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.710E-2</td>
<td>-5.263E-2</td>
</tr>
<tr>
<td>3</td>
<td>1.247E-1</td>
<td>-9.062E-2</td>
</tr>
<tr>
<td>5</td>
<td>2.205E-1</td>
<td>0.000E 0</td>
</tr>
<tr>
<td>7</td>
<td>1.858E-1</td>
<td>1.423E-1</td>
</tr>
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<td>9</td>
<td>6.727E-2</td>
<td>2.071E-1</td>
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<td>11</td>
<td>-4.837E-2</td>
<td>1.495E-1</td>
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<tr>
<td>13</td>
<td>-6.305E-2</td>
<td>4.581E-2</td>
</tr>
<tr>
<td>15</td>
<td>0.000E 0</td>
<td>0.000E 0</td>
</tr>
<tr>
<td>17</td>
<td>4.821E-2</td>
<td>3.503E-2</td>
</tr>
<tr>
<td>19</td>
<td>2.012E-2</td>
<td>8.654E-2</td>
</tr>
</tbody>
</table>

\[ f(t) = \sum_{n=1}^{\infty} a_n \cos \omega n t + b_n \sin \omega n t \]
chopper mount deflections were then computed from the time series.

RMS was then multiplied by the transfer function and then converted back to the time domain. The transfer function harmonic responses were calculated by taking the Fourier components of the unit torque function and scaling them to the right. Graphs of the right.

The response of the structure as a function of the torque frequency is represented as RMS deviations in torque about the x-axis. Responses near 80 and 200 Hz are apparent.

The Fourier Response plot indicates the magnitude of x-rotation (deltal) as a function of a unit amplitude. Lower left-hand plot indicates the magnitude of x-rotation. The Frequency Response shown in the lower left-hand plot indicates the magnitude of x-rotation. The Frequency Response shown in the lower left-hand plot indicates the magnitude of x-rotation.
The jitter estimates are close to the levels allowed in the optical error budget. With minor structural changes, the jitter values could possibly be reduced to very conservative levels so that the use of a nonrecirculation chopper can be seriously considered.

A conservative estimate for jitter is obtained by selecting the highest peaks of the response curves on the previous page and scaling them by the computed torque.

Expected maximum torques are computed for the original SORIA specifications by assuming a mirror.

Jitter Results
### STRUCTURAL EXCITATION

<table>
<thead>
<tr>
<th>Specification</th>
<th>Frequencies</th>
<th>Throw</th>
<th>Rise Time</th>
<th>MaxTorque</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-35 Hz</td>
<td>5 arcmin</td>
<td>5msec</td>
<td>5.5 N-m</td>
</tr>
<tr>
<td>2</td>
<td>1-10 Hz</td>
<td>20 arcmin</td>
<td>7msec</td>
<td>11.4 N-m</td>
</tr>
</tbody>
</table>

### JITTER RESULTS

<table>
<thead>
<tr>
<th></th>
<th>Jitter</th>
<th>Error Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation Spec.1</td>
<td>3.9 μRad</td>
<td>2.4 μRad</td>
</tr>
<tr>
<td>Spec.2</td>
<td>4.6 μRad</td>
<td></td>
</tr>
<tr>
<td>Decenter Spec.1</td>
<td>0.77 μm</td>
<td>1 μm</td>
</tr>
<tr>
<td>Spec.2</td>
<td>1.1 μm</td>
<td></td>
</tr>
</tbody>
</table>
The third concept was implemented in a single-axis form with great success by the designer of the performance.

Even slight misalignments substantially degrade the mass of the mirror and reaction mass. Apparent difficulties were encountered in precisely locating the axis of rotation at the center of the lever arms.

Concept two is an obvious solution to the problem. To achieve the maximum extremity with well-damped, also additional torque is required to move the lever arms. The momentary possibility of too much complexity in the system, care would have to be taken to make a closer look at the geometric details of a device. The lever and complexity of the design can be made to turn to zero for any optimum axis of rotation. Several disadvantages become apparent for this alternative in (1)

Possible solutions for rectangular moments in a two-axis design were to arms may be arranged in a radial pattern. A particularly useful in a two-axis design might be a plot of the moment generated in (1) by arms. One may have several different geometries, but the essence of the design is that a

Three concepts for rectangular designs are noted here:
REACTIONLESS CHOPPER CONCEPTS

MOMENTUM BALANCE WITH LEVERS

\[ \frac{\alpha}{\alpha_0} = \frac{J_3}{J_1} \]

DYNAMIC IMAGE

REACTION MASS

\[ \frac{J_2}{J_1} = \frac{k_i}{J_i} \]
The designer recommends the use of a two-axis feedback system with multiple mirror telescopes (MNT). This arrangement allows for precise control and reduces the number of problems associated with single-axis systems. The designer notes that the use of multiple mirrors significantly improves the system's performance, and increases the range of view. The primary challenge is to design a system that can handle the complexity of multiple mirrors, while maintaining a high level of precision. The designer suggests using a combination of feedback sensors and actuators to achieve this goal. A key feature of the MNT system is its ability to detect and correct for any misalignment, ensuring that the system remains stable and accurate. The designer also recommends the use of advanced control algorithms and signal processing techniques to further enhance the system's performance. Overall, the MNT system is a robust and effective solution for applications requiring high precision and reliability.
# Existing Chopper Systems

<table>
<thead>
<tr>
<th>Location</th>
<th>Mirror Ampl. P-P (Arcmin)</th>
<th>Transition Time (msec)</th>
<th>Frequencies (Hz)</th>
<th>Mirror Material &amp; Diam. (cm)</th>
<th>Mirror Mass (kg)</th>
<th>MOI (kg-m^2)</th>
<th>Actuator Type</th>
<th>Force &amp; No.</th>
<th>Chopper Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMT</td>
<td>2.1</td>
<td>3 (0-100%)</td>
<td>30</td>
<td>CORNING 2 7940 FUSED SILICA</td>
<td>1.3</td>
<td>&lt;.0045</td>
<td>CUSTOM-MADE RARE-EARTH VOICE COIL 2</td>
<td>2</td>
<td>SINGLE AXIS</td>
</tr>
<tr>
<td>KPNO</td>
<td>2</td>
<td>3</td>
<td>30</td>
<td>ZERODUR 40.6 3.8 @ CENTER 1.9 @ EDGE</td>
<td>3-5 ?</td>
<td>.09</td>
<td>CUSTOM-MADE MOVING COIL .68 (N-M)/AMP 4</td>
<td>4</td>
<td>DUAL AXIS REACTIONLESS ATTEMPT</td>
</tr>
<tr>
<td>PALOMAR</td>
<td>3.3</td>
<td>1.2 (10-90%)</td>
<td>83</td>
<td>BERYLLIUM 25.4 10.2 HOLE</td>
<td>1.2</td>
<td>.0062</td>
<td>COMMERCIAL ? VOICE COIL 10.4 N/AMP /ACT. 2</td>
<td>2</td>
<td>SINGLE AXIS REACTIONLESS &gt;99% EFFECTIVE</td>
</tr>
<tr>
<td>UKIRT</td>
<td>72</td>
<td>7.5</td>
<td>0-15</td>
<td>ALUMINUM 75 3 THICK PLUS FRAME</td>
<td>7.5</td>
<td>?</td>
<td>LING SHAKERS VOICE COIL 4</td>
<td>4</td>
<td>DUAL AXIS</td>
</tr>
<tr>
<td>LSMC</td>
<td>3.5</td>
<td>3.2 (10-90%)</td>
<td>10</td>
<td>ZERODUR 40.6 5 THICK</td>
<td>9</td>
<td>&lt;.09</td>
<td>CUSTOM-MADE ELECTRODYNAMIC TYPE 3</td>
<td>3</td>
<td>DUAL AXIS REACTIONLESS 95% EFFECTIVE</td>
</tr>
<tr>
<td>IDEAL SOFIA</td>
<td>5</td>
<td>5</td>
<td>1-35</td>
<td>TBD 30.5 2.5 THICK</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>DUAL AXIS REACTIONLESS IF NECESSARY</td>
<td></td>
</tr>
</tbody>
</table>

4-61
Forwarded, a very accurate trajectory can be followed, virtually eliminating any overshoot.
# EXISTING CHOPPER SYSTEMS (CONT'D)

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>CHOPPER SIZE ENVELOPE</th>
<th>FLEXURE STYLE</th>
<th>SENSOR TYPE</th>
<th>OPERATING CURRENT VOLTAGE (AMPS,VOLTS)</th>
<th>CONTROLLER TYPE/COMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMT</td>
<td>22.8m x 7.8m w/o focusing</td>
<td>FLEX PIVOTS</td>
<td>(POS) SCHAERVITZ &amp; HP LVDT'S, (VEL) MOVING COIL</td>
<td>10 24</td>
<td>ANALOG LEAD/LAG</td>
</tr>
<tr>
<td>KPNO</td>
<td>40.6 x 7.6 w/o focusing</td>
<td>BENDIX FLEX PIVOTS, U-JOINT CONFIGURATION</td>
<td>(POS) SCHAERVITZ LVDT, (VEL) SCHAERVITZ</td>
<td>8 48</td>
<td>ANALOG LEAD/LAG TYPE 2</td>
</tr>
<tr>
<td>PALOMAR</td>
<td>25.4 x 15.2 w/o focusing</td>
<td>FLEX PIVOTS</td>
<td>(POS) SCHAERVITZ LVDT (VEL) DERIVED FROM POS</td>
<td>?</td>
<td>ANALOG LEAD/LAG</td>
</tr>
<tr>
<td>UKIRT</td>
<td>75.0 x 40 w/o focusing</td>
<td>FLEX PIVOTS</td>
<td>(POS) LVDT TYPE (VEL) ?</td>
<td>22/ACTUATOR 24</td>
<td>DIGITAL ADAPTIVE 6809 uP</td>
</tr>
<tr>
<td>LSMC</td>
<td>40.6 x 22.3 w/o focusing</td>
<td>MIRROR UNSUPPORTED AT CENTER, FLEXURES AT ACTUATOR PIVOT</td>
<td>(POS) ? (VEL) DERIVED FROM POS</td>
<td>48 28</td>
<td>ANALOG PID TYPE 1</td>
</tr>
<tr>
<td>IDEAL SOFIA</td>
<td>30.5 x 35.5 w/1 focusing</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>
Preliminary results show that jitter may be very close to the allowable amount.

Structural calculations indicate that "a reactionless system may not be a requirement."

A simulation which includes the flexibility of the motor-mirror junction indicates that there is a significant advantage gained in controlling the chopper if velocity feedback is taken from the motor rather than the mirror. Position feedback should be taken from the mirror.

Using a yoke with controllable gain eliminates the motor-mirror flexure.

Pay particular attention to the stiffness of the motor-mirror junction.

Keeping the mechanism simple.

Problems, care should be taken to resolve this problem by:

Experience of others indicates that internal structural resonances cause severe jitter.

Conclusions and Recommendations:
Conclusions and Recommendations (Contd)

- To keep the chopper mechanism simple, a separate focus dither mechanism is recommended.
- Analog compensators have proven to be adequate for chopper control. Digital control is possible.
- Accurate tracking of the desired transition profile is desirable to minimize the torque required and keep the electronics and actuators from saturating.
- Assuming that Image Motion Compensation is not a requirement, a single-axis chopper with rotation may be adequate, and can be designed with existing technology.
- A two-axis design is also feasible with the added complexity of ensuring that the axes of rotation are true. A reactionless two-axis system may be difficult to design.
- Should a reactionless design become a firm requirement, a single-axis design based on the "Reaction Mass" concept is recommended in view of the success obtained with the Palomar chopper system.
This section (4.2) describes the optical system and the instrument's structure, which are addressed in Section 4.3. The primary mirror support structure is addressed at the end of this section. The portion of the structure that supports the primary mirror is connected to the instrument's support structure, which is described in Section 4.3. The structure includes all structural elements that are isolated from the telescope structure, described as follows.

The SOFIA telescope structure includes all structural elements that are isolated from the instrument's support structure.
SOFIA TELESCOPE STRUCTURE - SCOPE

- TELESCOPE SUPPORT STRUCTURE/CENTERPIECE
- PRIMARY MIRROR SUPPORT STRUCTURE
- METERING STRUCTURE (TUBE)
- SECONDARY MIRROR SUPPORT STRUCTURE/HEADRING AND SPIDERS
- INSTRUMENTATION AND COUNTERWEIGHTING STRUCTURE/INSTRUMENT FLANGE
- AIRBEARING SPHERICAL SHELL AND CONNECTING STRUCTURE
Temperature loads, de-center, and de-tilt of the secondary mirror refer to the primary under gravity, dynamic and mounting in the structure will be within values specified for the error budget. This includes defocus, movement of optical components.

The telescope structure must have very high dimensional stability so movement of optical components necessary to avoid instability problems in the pointing control system.

The telescope structure must have a first mode natural frequency that is high enough to avoid structural resonance induced by cavity wind loads or aircraft vibrations. The high first mode is also volume including all desired movements of the telescope. The physical size of the telescope structure must be large enough to rigidly support optics for 3.0 m / 1 telescope. However, the size of the structure must fit within the available aircraft cavity.

The telescope structure should not weigh more than 70,000 lbs, including the weight of the primary and secondary structure. The entire telescope system has been given a weight budget of 30,000 lbs. The telescope structure as defined in the scope represents approximately 2/3 of the telescope system. Therefore, the telescope structure and stiffness or dimensional stability.

There are three major requirements for the SORIA telescope structure, weight, size, and stiffness or
SOFIA TELESCOPE STRUCTURE - MAJOR REQUIREMENTS

- WEIGHT: TELESCOPE STRUCTURE INCLUDING THE OPTICS NOT TO EXCEED THE WEIGHT BUDGET

- SIZE/VOLUME: TELESCOPE STRUCTURE MUST BE LARGE ENOUGH TO SUPPORT 2.75-3M OPTICS AND COMPACT ENOUGH TO FIT IN AIRCRAFT CAVITY

- STIFFNESS/RIGIDITY: FIRST MODE NATURAL FREQUENCY MUST BE HIGH ENOUGH TO AVOID RESONANCE AND CONTROL PROBLEMS

MOVEMENT OF OPTICAL COMPONENTS MUST BE WITHIN LIMITS OF ERROR BUDGET
The instrument frame and centerpiece are connected to the structure with a welded plate. The instrument frame is also a welded plate structure. The arrangement of counterweights is provided with movable weights located on the inner lens. This allows the structure to be balanced around the center of the instrument with less weight overall.

The centerpiece is mounted to the bottom of the instrument tube with a plate. The secondary mirror is mounted to the top of the instrument tube with a plate. The primary mirror support is a bonded plate structure. This is achieved done to provide a light, stiff, and be constructed of materials with high coefficient of thermal expansion such as aluminum.

The centerpiece provides a very stiff structure with minimal weight. This type of design is similar to the KAO design, except that the plates have varying thickness. This provides the main support structure for the telescope. It is a welded or bonded plate structure for the SOFIA Telescope Conceptual Design.
2 inches thick. No attempt is made to reduce the weight of the Instrument Flange since it acts as part of the counterweight.

The Instrument Flange is modeled as an aluminum plate structure with internal stiffeners. The plate is 0.045 inches thick. This was done using an optimization routine to keep the first mode natural frequency as high as possible while minimizing the weight.

The centerplate is modeled as an aluminum plate structure with internal stiffeners. The plate is 0.025 inches thick. This was done using an optimization routine to keep the first mode natural frequency as high as possible while minimizing the weight.

Components of structural analysis model.
COMPONENTS OF STRUCTURAL MODEL

CENTERPIECE

METERING TUBE
HEADRING/SPIDER

AIRBEARING SHELL

INSTRUMENT FLANGE

PRIMARY MIRROR SUPPORT
The composite sandwich material that was used extensively for modeling components of the telescope structure was chosen in part to take advantage of unequal coefficients of thermal expansion as well as how thermal expansion and weight.

The influence on the design efforts, and ply orientations other than 0°, 45°, and 90° should be used in future design efforts.
HONEYCOMB CORE COMPOSITE SANDWICH MODEL

1.00"

0.07"

8 PLYS @ 0°
4 PLYS @ ±45°
2 PLYS @ 90°

+45°
0°
-45°
90°
Integration of the gyroscope and tracker telescope. Other concentrated masses are used to represent the secondary mirror, tracker telescope, and counterweights.

Elemental inertial masses add little mass to the structure.

The primary mirror mass is modeled as a concentrated mass with principal moments of inertia:

\[ I_{xx} = I_{yy} = I_{zz} \]

The integrated structural model is made up of the components discussed previously. All of the
Receptiveness of reflector would be necessary. This was done to determine if and to what degree a chopper input torque was determined. Also, frequency response of the heading and signals to secondary function between longer locations and secondary mirrors, de-focus, de-center, and de-elevation. This was done to investigate the stability of secondary mirrors at 60 degrees of elevation. This was applied to the structure with the telescope oriented at 25 degrees of elevation and a frequency of 100 Hz. 

A dynamic load consisting of a gravity force was applied along with a frequency function with a frequency of 25 degrees of elevation and a frequency of 100 Hz. 

Predicting pointing control response and structural resonance problems. The other modes are useful for predicting pointing control response and structural resonance problems. The other modes are useful. The first mode frequency is a measure of structural stiffness. The other modes are used for additional analysis for chopper and control system design investigations.

Analysis of the telescope structure model was done using NASTRAN. The types of analysis performed were normal mode, deflection under gravity, dynamic loads, temperature loads, and additional load models. The types of analysis performed were normal mode, deflection under gravity, dynamic loads, temperature loads, and additional load models.
ANALYSIS OF SOFIA TELESCOPE STRUCTURE

- NORMAL MODES ANALYSIS
- STATIC/GRAVITY LOAD OVER 20° TO 60° ELEVATION RANGE
- DYNAMIC LOAD OF .25g ACCELERATION AT 1 Hz
- TEMPERATURE LOAD FOR A 25° F CHANGE
- ADDITIONAL ANALYSIS FOR OTHER SUBSYSTEMS STUDY
The parameters for de-focus, de-center, de-tilt, and line of sight were determined from error budget structure. The first mode natural frequency goal of 25 Hz was set after initial modes showed that values significantly higher than those would not be achievable within weight and size restrictions for the telescope system and as described in the major requirements. The goal weight of the structure is 20,000 lb, including the optics. This is approximately 2/3 of the telescope structure goals and parameters.
TELESCOPE STRUCTURE GOALS AND PARAMETERS

<table>
<thead>
<tr>
<th>ITEM</th>
<th>GOALS/PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEIGHT OF STRUCTURE INCLUDING OPTICS</td>
<td>20,000 LBS</td>
</tr>
<tr>
<td>FIRST MODE NATURAL FREQUENCY</td>
<td>25 Hz</td>
</tr>
<tr>
<td>SECONDARY TO PRIMARY DE-FOCUS, STABILITY LIMIT</td>
<td>5 MICRON</td>
</tr>
<tr>
<td>SECONDARY TO PRIMARY DE-CENTER, ABSOLUTE LIMIT</td>
<td>50 MICRON</td>
</tr>
<tr>
<td>SECONDARY TO PRIMARY DE-CENTER, JITTER LIMIT</td>
<td>1 MICRON</td>
</tr>
<tr>
<td>SECONDARY TO PRIMARY DE-TILT, ABSOLUTE LIMIT</td>
<td>60 ARCSEC</td>
</tr>
<tr>
<td>SECONDARY TO PRIMARY DE-TILT, JITTER LIMIT</td>
<td>.5 ARCSEC</td>
</tr>
</tbody>
</table>
The 8th mode, at 50.8 Hz, is a twisting mode. It is so described because the structure twists about the extension axis of the telescope.

The 7th mode, at 33.4 Hz, is another vertical dumbbell mode. However, in this mode, the secondary spiders extend upward in the opposite direction of travel from the telescope.

The 5th mode, at 27.5 Hz, is a vertical dumbbell mode. In this mode the secondary spiders extend upward in the same direction of travel as the telescope.

A dumbbell shape, bending laterally about the spherical sphere, is a vertical dumbbell shape, bending laterally about the spherical sphere. The 4th mode, at 27.1 Hz, is a vertical dumbbell mode. It is so described because the structure takes on a dumbbell shape, bending laterally about the spherical sphere.

The lowest natural frequency for the structure is 27.1 Hz. The mode shapes for the four modes of interest are described below.

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The lowest natural frequency for the structure is 27.1 Hz. The mode shapes for the four modes of interest are described below.
NORMAL MODES ANALYSIS

<table>
<thead>
<tr>
<th>MODE</th>
<th>FREQUENCY, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>4TH, LATERAL DUMBELL MODE</td>
<td>27.1</td>
</tr>
<tr>
<td>5TH, VERTICAL DUMBELL MODE</td>
<td>27.5</td>
</tr>
<tr>
<td>7TH, VERTICAL DUMBELL MODE</td>
<td>33.4</td>
</tr>
<tr>
<td>8TH, AXIAL TWIST MODE</td>
<td>50.8</td>
</tr>
</tbody>
</table>

(FIRST THREE MODES ARE RIGID BODY MODES; 6TH MODE HAS LOCALIZED MOTION ONLY)
This represents a de-focus stability of 5.2x microns equivalent an error budget stability limit of 5 microns.
The de-focus range from 3.97 microns at 60° to 5.2x microns at 20°. Therefore, the curve represents a de-focus vs the telescope is elevated at 40° degree elevation angle. Therefore, the curve represents a de-focus vs elevation angle curve. The de-focus vs elevation angle curve was constructed assuming that all de-focus is removed with the results for de-focus stability vs elevation angle.
DE-FOCUS VS ELEVATION ANGLE

Maximum Allowable De-focus is 5 micron
9.1 microns compared to an error budget absolute limit of 50 microns.

At 60° elevation, it is evident, however, the de-center stability due to elevation changes is 5.1 microns at 70°. Therefore, the de-center stability shown as positive. The magnitude of de-center ranges from 7.9 microns directions, so all de-center is shown as positive. The magnitude of de-center is calculated as the root sum square (RSS) for de-center in the X and Y directions.

The de-center vs elevation angle curve is constructed in the same manner as the de-focus curve. Therefore, for de-center vs elevation angle...
DE-CENTER VS ELEVATION ANGLE

Max Allowable De-center is 50 micron
Absolutes limit of 60 Arcsec.

The stability of the-de-ellipse due to elevation angle changes is 0.28 Arcsec compared to an error budget.

The de-ellipse ranges from 0.28 Arcsec at 90 degrees elevation to 0.15 Arcsec at 20 degrees. Therefore, the de-ellipse has been combined in the same manner as the de-center curve.

Also, X-axes and Y-axes have been constructed in the same manner as the de-focus curve.

Results for de-Elevation Angle
DE-TILT VS ELEVATION ANGLE

Max Allowable De-tilt is 60 arc-sec
The line of sight (LOS) change due to the dynamic load is 6.65 x 10^{-2} arcsec. The jitter limit for LOS jitter is 0.5 arcsec.

The de-center jitter for the dynamic load is 4.35 x 10^{-3} arcsec. The error budget limit for de-center is 1 micron. The de-center jitter for the dynamic load is 9.8 x 10^{-2} microns compared to the error budget stability limit of 5 microns.

The focus error for the dynamic case is 1.9 x 10^{-4} microns. The de-focus, de-center, and de-jitter for the secondary mirror relative to the primary mirror were determined for the dynamic loading case.

Results for dynamic load at 76.2 Hz.
# RESULTS FOR DYNAMIC LOAD OF .25g AT 1 Hz

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>RESULT</th>
<th>STABILITY LIMIT</th>
<th>JITTER LIMIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE-FOCUS</td>
<td>1.9 x 10^{-4} MICRON</td>
<td>5 MICRON</td>
<td>-</td>
</tr>
<tr>
<td>DE-CENTER</td>
<td>9.8 x 10^{-2} MICRON</td>
<td>-</td>
<td>1 MICRON</td>
</tr>
<tr>
<td>DE-TILT</td>
<td>4.36 x 10^{-5} ARCSEC</td>
<td>-</td>
<td>.5 ARCSEC</td>
</tr>
<tr>
<td>LOS CHANGE</td>
<td>6.65 x 10^{-2} ARCSEC</td>
<td>-</td>
<td>.15 ARCSEC</td>
</tr>
</tbody>
</table>

ALL PARAMETERS ARE WITHIN LIMITS
The de-focus stability for temperature load is well.

The de-focus, de-center, and de-tilt of the secondary mirror relative to the primary mirror were determined for the temperature load as well.

The de-focus stability for temperature load is 5 microns.

The de-focus, de-center, and de-tilt of the primary mirror were determined for the temperature load as well.

The de-focus stability is 0.71 arcsec, compared to the error budget absolute limit for de-tilt of 60 arcsec.

The de-center thermal stability is 8.0 microns, compared to the error budget absolute limit for de-center.
# RESULTS FOR TEMPERATURE LOAD OF 25°F CHANGE

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>RESULT</th>
<th>STABILITY LIMIT</th>
<th>ABSOLUTE LIMIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE-FOCUS</td>
<td>70.5 MICRON</td>
<td>5 MICRON</td>
<td>--</td>
</tr>
<tr>
<td>DE-CENTER</td>
<td>8.01 MICRON</td>
<td>--</td>
<td>50 MICRON</td>
</tr>
<tr>
<td>DE-TILT</td>
<td>0.71 ARCSEC</td>
<td>--</td>
<td>60 ARCSEC</td>
</tr>
</tbody>
</table>

DE-FOCUS EXCEEDS STABILITY LIMIT BY A FACTOR OF 16
requirements can be determined from the MOI matrix. However, a relative idea of the mass distribution and pointing control torque moment information. There is no good value of parameter for the MOI matrix, so it is presented primarily for the primary and secondary mirrors, counterweights, tracker telescope, and absorbing spherical shell. The moment of inertia matrix for the structure is as shown in the table. The values include the mass.
## Telescope Structure Moment of Inertia

<table>
<thead>
<tr>
<th>MASS AXIS</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>$1.265 \times 10^8$</td>
<td>$4.576 \times 10^5$</td>
<td>$3.846 \times 10^5$</td>
</tr>
<tr>
<td>Y</td>
<td></td>
<td>$4.232 \times 10^7$</td>
<td>$-1.004 \times 10^7$</td>
</tr>
<tr>
<td>Z</td>
<td>SYM</td>
<td></td>
<td>$1.374 \times 10^8$</td>
</tr>
</tbody>
</table>

All values are in units of lb-in$^2$
Finally, the conceptual structure design is large enough to support optics for a 2 m, f/1 telescope, and temperature were encountered. The conceptual design would require re-designing the optics during slight tilting if changes in cavity air temperature are not within stability limits for a temperature change 20°F on the entire structure. However, the de-focus is not within stability limits for the temperature change. Therefore, de-focus, de-center, de-tilt, and line of sight are within stability limits for dynamic loads on the structure during slight tilting. This means that no adjustment of the optics is necessary due to large changes in pointing elevations. The first non-zero normal mode frequency is 72.7 Hz. This is above the minimum goal of 25 Hz. It is believed that the stiffness of the structure as represented by the ZJ, J. H. It is above the minimum goal of 25 Hz. It is followed by the eigenvalue resonance as well as pointing control problems. The results of this study on the structure are summarized in the following paragraphs.
TELESCOPE STRUCTURE SUMMARY AND CONCLUSIONS

• WEIGHT ESTIMATE OF CONCEPTUAL DESIGN IS 13,750 LBS NOT INCLUDING AIRBEARING SPHERE

• 1ST NON-ZERO NORMAL MODE IS 27.1 Hz

• DE-FOCUS, DE-CENTER, AND DE-TILT STABILITY LIMITS ARE MET FOR FULL RANGE OF ELEVATION ANGLES

• DE-FOCUS, DE-CENTER, DE-TILT, AND LOS JITTER LIMITS ARE MET FOR DYNAMIC LOAD

• DE-CENTER AND DE-TILT STABILITY LIMITS ARE MET FOR TEMPERATURE LOAD; DE-FOCUS LIMIT CURRENTLY NOT MET

• CURRENT CONCEPTUAL DESIGN WILL SUPPORT 3M OPTICS
concentric telescoping structure is reasonably high, reducing the possibility of such an occurrence.

Overall structural concept appreciably improves the upper portion of the metaling tube with stress would not change the structure is better, reflecting the upper portion of the metaling tube with stress could not change the structure is better, reflecting the upper portion of the better design on the structure is an issue as well. Because cavity wind loads on the structure.

Although evaluation of wind loads on the metaling tube could suggest that a truss type metaling structure.

Spiders is an important issue as well.

This is also substantial, surface area compared to a truss type metaling structure. Wind loads on the structure most important when considering on the evaluation of the area is applied to the structure. This is the wind loading issue is that of not having representative wind loads applied to the structure. This is the material issue.

The issue of transient temperature conditions cannot be addressed with the material problem is.

Design pressure it has not been addressed here.

Concentric telescoping structure is not considered to be an important issue. Therefore the issue of transient temperature loads is not considered to be an important issue. The radial contraction of expansion of the metaling tube is less than that of the aluminum. The composite metaling tube is greater than that of the aluminum concentric. However, under transient temperature conditions the temperature structure is.

The composite material issue is a matter of by applying design. Although the material used for the structure.

Tempertature loadings that represent transient state conditions as predicted by the thermal analysis have not been applied to the structure.

There are two issues regarding temperature stability. First, the composite material used to model the temperature change can be as high as 20°F, more work is needed in this area to predict possibility.

The de-focus stability requirements for the current model can be met if the temperature change.
TELESCOPE STRUCTURE OPEN ISSUES

- TEMPERATURE STABILITY:
  - IMAGE STABILITY DUE TO TEMPERATURE
    CHANGE NEEDS FURTHER STUDY
  - TRANSIENT TEMPERATURE LOAD CONDITIONS HAVE NOT BEEN
    APPLIED TO THE STRUCTURE

- WIND LOADING:
  - REPRESENTATIVE WIND LOADS HAVE NOT BEEN DEVELOPED
    OR APPLIED TO STRUCTURE
Align the object with the desired mirror configuration. The mirror was positioned to the desired figure with the axis vertical and with the backplate plane. For the calculation of mirror distortion, it was assumed that the mirrors were perfect, meaning that the mirrors were not subjected to any deformation due to thermal gradients, gravity, or any other external forces.

Guidelines used for maximum time variations of the axial position of the mirror and mirror tilt are 0.5 cm and 0.05 arcsec, respectively.

The right-hand sketch should correspondingly be ≤ 0.07 cm and the rms axial distortion along any straight line through the points along any curve of constant radius (as illustrated on the upper left-hand sketch) in the chart should be ≤ 0.07 cm. The root mean square of distortion in the mirror tilt direction from the desired figure at points along any curve of constant radius (as illustrated on the upper left-hand sketch) in the chart should be ≤ 0.07 cm.

The following criteria for acceptable distortion have been used for evaluation purposes:

- Air pressure variation (static and dynamic)
- Telescope and turntable eccentricities and vibrationally deforms the mirror support frame
- Air pressure variation (static and dynamic)
- Mirror structure
- Dynamic loading of the mirror of its support frame, where the sources of dynamic loading are:
  - Temperature changes and temperature gradients in the mirror support frame
  - Temperature changes and temperature gradients in the mirror support frame
  - Elevation angle (±20° to ±60°) change
  - Gravity and changes in the direction of gravity with respect to the mirror axis due to changing elevation angle
  - Raction that the mirror figure requirements are met, except that no other mirror figure distortion are:

This subsection comprises a design description of a mirror support system for the baseline SPOJ ULT primary mirror system support platform - Introduction.
TELESCOPE STRUCTURE OPEN ISSUES

- TEMPERATURE STABILITY:
  - IMAGE STABILITY DUE TO TEMPERATURE CHANGE NEEDS FURTHER STUDY
  - TRANSIENT TEMPERATURE LOAD CONDITIONS HAVE NOT BEEN APPLIED TO THE STRUCTURE

- WIND LOADING:
  - REPRESENTATIVE WIND LOADS HAVE NOT BEEN DEVELOPED OR APPLIED TO STRUCTURE
Information regarding the primary mirror concept is found in Section 4.1.

More specifically, and outer ring, "fill-bonded" to an inner square web of the same material. More literally, the primary mirror consists of a ULE facet plate, which was used to develop the support system concept. This mirror design is based on an extension of the baseline SOFIA primary mirror, which illustrates the dimensions and construction of the "baseline" primary mirror.
BASELINE SOFIA PRIMARY MIRROR - 3.0 m DIAMETER SQUARE WEB

0.5 in.
INNER RING

0.5 in.
FACE PLATE

0.5 in.
BACK PLATE

0.5 in.
OUTER RING

0.075 in.
WEB

0.150 in.
POST

3.00 in.

3.00 in.
The chart shows the effect of the support points on the distortion budget. This system comprises 48 support points and features a suitable reaction to the distortion budget. The arrangement of the support points was designed to be a section based on one arrangement only. The distortion from this arrangement was studied to be a section. Various distributions of the applied force at the support points were examined. The results given in this section describe the distribution of the applied force on the radial position of the support points. The total number of support points was varied from 9 to 64, and various spatial distributions of supports and radial position of the support points were evaluated for a variety of axial support arrangements. The total mirror distortion was evaluated for each interface by a pneumatic piston, one piston for each support point (details of mirror response).

The axial support system comprises an array of supports that interface with the backplate of the mirror. At each interface location, a predetermined force is applied by the support member to the mirror. The support member is rigidly connected to the backplate, and the remaining interface areas are subject to a pure shearing stress (hinge) to the backplate.
AXIAL SUPPORT ARRANGEMENT

FORCE APPLIED AT SUPPORT POINTS
FOR ELEVATION ANGLE OF 40 DEGREES

<table>
<thead>
<tr>
<th>RADIUS, in. (cm)</th>
<th>FORCE, lb (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.2 (51.2)</td>
<td>19.4 (86.3)</td>
</tr>
<tr>
<td>35.3 (89.7)</td>
<td>28.8 (128.1)</td>
</tr>
<tr>
<td>54.1 (137.4)</td>
<td>52.0 (231.3)</td>
</tr>
</tbody>
</table>

LEGEND
○ AXIAL SUPPORT LOCATION

NOTE: AXIAL GRAVITY COMPONENT IS INTO THE PAGE
The most severe distortion due to gravity in the axial direction is for the elevation angle of 60°. The mirror tilt is 0.06 mm. The largest rms distortion along radial spokes is 0.06 mm, and the rms for radial of 115 cm and 129 cm. The largest rms distortion along circumferential curves (curves of constant radius) indicates a worst-case of 0.02 mm (at the curves) from polynomials along circumferential curves. Various calculations of root mean square distortion have been obtained. Calculations of rms distortion will not be achievable with significantly lower than 48 axial supports.

The axial support configuration has not been optimized with respect to mirror figure (or image). The two types of distortion increase the magnitude of footprint distortion, and the results given represent a compromise between the two types of footprint distortion. The results given represent a compromise between the two types of distortion. The results shown are small compared to typical distortion. The magnitude of the axial distortion is small compared to normal distortion. Although the magnitude of the axial...
AXIAL DISTORTION DUE TO AXIAL GRAVITY COMPONENT

<table>
<thead>
<tr>
<th>CONTOUR #</th>
<th>DISTORTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.090 μm</td>
</tr>
<tr>
<td>10</td>
<td>+0.090 μm</td>
</tr>
</tbody>
</table>

CONTOUR INTERVAL: 0.018 μm

NOTES:
• AXIAL GRAVITY COMPONENT IS INTO THE PAGE.
• MINUS INDICATES DEFLECTION INTO THE PAGE.
The component of gravity perpendicular to the mirror axis (the transverse component) causes a mirror to deflect. Support at points at 90° is best. For an elevation angle of 40° deflections, the theoretical support must be varied with elevation angle. In this case, the mirror location was found to be minimum when the multitudes of the applied force at each contact point were equal to the weight of the mirror. The mirror support points are located at the plane of the mirror. The two contact points are opposite to the component of gravity in the plane of the mirror. In this case, the direction of the forces applied to the mirrors were opposite to the direction of the deflection of the mirror. An illustration of the transverse support configuration which provided the best overall result is shown below.
The elevation angle that produces the largest distortion is 20 degrees. A table showing worst case RMS axial distortion (in mm) due to transverse gravity loads:

<table>
<thead>
<tr>
<th>Elevation Angle, Deg.</th>
<th>RMS Axial Distortion (in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>0.08</td>
<td>0.14</td>
</tr>
<tr>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>20</td>
<td>40</td>
</tr>
</tbody>
</table>

Worst Case RMS Axial Distortion (in mm) due to Transverse Gravity Loads

Contours are for the transverse direction. The contours are for the median elevation angle of 0.627. Elevation angles on the opposite face indicate mirror distortion in the axial direction due to the component of gravity in the transverse direction. The component of gravity in the transverse direction produces a measurable effect on the mirror.
AXIAL DISTORTION DUE TO TRANSVERSE GRAVITY COMPONENT

<table>
<thead>
<tr>
<th>CONTOUR #</th>
<th>DISTORTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.254 μm</td>
</tr>
<tr>
<td>10</td>
<td>+0.254 μm</td>
</tr>
</tbody>
</table>

CONTOUR INTERVAL: 0.051 μm

NOTE: MINUS INDICATES DEFLECTION INTO THE PAGE.
Worst Case RMS Distortion (in µm) due to Gravity Loads

Radial, Circumferential, Elevation Angle - deg

| 60°0 | 0.10 | 0.09 | 0.09 |
| 60°0 | 1.00 | 0.14 | 0.17 |
| 60°0 | 0.10 | 0.17 | 2.0 |

Radial directions are 6°0.17 µm and 0.10 µm, respectively, both below the 0.21 µm guideline budget.

Improvements can be achieved without unduly compromising the transverse system.

It is evident that the transverse component of Gravity dominates the overall distortion. Less effort

or 40 degrees.

The contours are for the median elevation angle effect of axial and transverse components of Gravity. The contours are for the combined effect of axial and transverse Gravity components

Mirror Axial Distortion due to the Combined Effect of Axial and Transverse Gravity Components
AXIAL DISTORTION DUE TO GRAVITY

CONTOUR #   DISTORTION

1       -0.279 µm
10      +0.279 µm

CONTOUR INTERVAL: 0.056 µm

TRANSVERSE GRAVITY COMPONENT

NOTES:
- AXIAL GRAVITY COMPONENT IS INTO THE PAGE.
- MINUS INDICATES DEFLECTION INTO THE PAGE.
larger than about 1/4 in. movement.

Temperature variations (detail B shown in next section) mirror output is stated to be no
less than 6°C. After examining the effects on support frame deformation caused by gravity load and
environmental conditions (see reference I). Our tests on the test rig at the University of Pennsylvania
have shown that the effect due to environmental condition cannot be neglected.

In reality, the effect of gravity load will be affected by deformation of the support frame. In
reality, the effect of gravity load will be affected by deformation of the support frame. In
reality, the effect of gravity load will be affected by deformation of the support frame. In
reality, the effect of gravity load will be affected by deformation of the support frame. In
reality, the effect of gravity load will be affected by deformation of the support frame. In
reality, the effect of gravity load will be affected by deformation of the support frame. In
derailment, position is shown on the opposing page. Position displacement is accompanied by a
change in the pneumatic position in operational (uncompressed) position and controlled

Required support force variations with elevation angle are readily controlled.

High precision position on the mirror to support frame linkage is not required.

Deformation (bending) of the support frame due to gravity load changes (elevation angle)

Thermally induced differential displacements between the mirror and support frame

Thermal unevenness is relatively insensitive to

For SOPV, the primary advantages of pneumatic support are that:

used for a number of telescope applications, including some of the latest NOAO 4 meter, Herzog 4.5 meter, etc.,

earlier mechanical linkage methods, and in recent years pneumatic-based mirror supports have been

Mirror support forces, as mentioned above, are applied to the mirrors through a system of pneumatic

Pneumatic linkage between mirror and support frame.
CROSS-SECTION OF PNEUMATIC PISTON

MIRROR BACKPLATE
ELASTOMER DIAPHRAGM
CLAMP
SUPPORT FRAME UPPER PLATE

COLLAPSED (UNPRESSURIZED) POSITION
OPERATIONAL (PRESSURIZED) POSITION

It is important for the elastomeric diaphragm (shown on the sketch of the pneumatic piston) to

A mirror (reference 1) showed the distortion to be insufficient for the aperture point hex-core

The piston also imparts an undetectable transverse force on the mirror when it is displaced in the

An illustration of mirror figure distortion caused by a force error of 1/16 at two support points is

Pneumatic Linkage (cont'd)
AXIAL DISTORTION DUE TO LOCAL FORCE ERROR

CONTour #  DISTORTION
 1  -0.000 µm
 10 +0.090 µm

ConTouR INTERVAL: 0.009 µm

NOTES:
* AXIAL GRAVITY COMPONENT IS INTO THE PAGE.
* MINUS INDICATES DEFLECTION INTO THE PAGE.
<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Weight (kg/m²)</th>
<th>Volume (m³/m²)</th>
<th>Weight Volume (m²/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>45 (1200)</td>
<td>264</td>
<td>1.75</td>
<td>92.7</td>
</tr>
<tr>
<td>Graphite</td>
<td>44.5 (1200)</td>
<td>260</td>
<td>1.5</td>
<td>174</td>
</tr>
<tr>
<td>Epoxy</td>
<td>44.5 (1200)</td>
<td>250</td>
<td>1.3</td>
<td>192</td>
</tr>
<tr>
<td>Graphite/Epox</td>
<td>44.5 (1200)</td>
<td>250</td>
<td>1.3</td>
<td>192</td>
</tr>
</tbody>
</table>

Support Frame Characteristics - Graphite/Epox vs. Aluminum

Column 5 may produce an aluminum frame. The weight penalty with aluminum is significant, and it is possible that displacement of 0.8 mm in bending, resonance frequency, and torque frame overall. While in aluminum frame would be completely ineffective, it can be seen from the table below. The baseline support frame is constructed of Graphite/Epox composite, although an aluminum frame of identical configuration was analyzed in the internal. The baseline support frame is illustrated on the opposite page. The baseline support frame is constructed of Graphite/Epox composite, and cost, weight, and volume (geometric envelope) are also compared on adefinitive design. The support frame was designed to minimize these effects, but constraints on structural and cost performance contributed to the final design.
WEB STRUCTURE OF MIRROR SUPPORT FRAME
(UPPER PLATE NOT SHOWN)

MATERIAL FOR BASELINE — GRAPHITE/EPOXY

WEB STRUCTURE
THICKNESS = 0.25 in.
HEIGHT = 16.5 in.

LOWER PLATE
THICKNESS = 0.5 in.
I 4-120

Scans of a mirror, stresses should be accurately evaluated for all credible levels of out-of-plane acceleration. If the mirror stress due to the effect of a maximum internal stress condition is expected to be a critical component of the mirror, then the mirror will be designed to operate under an external stress condition, where the mirror is subjected to a critical stress condition. It is assumed that all internal stresses are considered.

Stress values should be evaluated through high fidelity modeling of the mirror. Because of the high accuracy small models, more accurate estimates can be provided by considering a typical mirror web box section and web geometry.

Primary Mirror Pressures

Pressures indicate that the effect of the mirror will be small, a further examination is warranted. Estimates indicate that the resulting flow will not contribute to primary mirror distortions, and while preliminary, estimates are warranted. Monte Carlo analysis is necessary, to which the induced dynamic distortions, although more investigation into order of magnitude of the above mentioned axial displacements, although more investigation into the relative dynamic distortion effects are small. Transverse displacements appear to be of the same magnitude.

While a more detailed analysis with improved modeling is still to be performed, preliminary estimates were 0.65 mm, with a 0.001 mm descent.


Dynamic Distortion and Dynamic Displacement of Primary Mirror
CONCLUSIONS: PRIMARY MIRROR SUPPORT SYSTEM

- Preliminary analysis shows that mirror figure guidelines with respect to gravity induced distortion can be met with a mirror support system comprising 48 axial supports and 12 transverse supports, where the transverse supports are located along the outer perimeter of the mirror. It is thought that the guidelines cannot be met with significantly fewer than 48 axial support points.

- It has been shown that existing pneumatically-based mirror-to-support frame interface techniques are capable of maintaining mirror support loads within a tolerance that satisfies mirror figure requirements:
  - For support frame deformation (bending) changes that occur over the elevation angle range (this applies to either the baseline graphite/epoxy support frame or an aluminum support frame)
  - For thermally induced distortion that will occur in the baseline support frame

With the qualifications that:

- Mirror distortion caused by thermally induced differential displacements between the baseline support frame and mirror in the transverse direction have not been analyzed for the baseline mirror, but have been shown to be negligible for similar mirrors. (There is some doubt whether mirror figure could be maintained with an aluminum support frame.)

- There is some concern whether commercially available diaphragms proven for mirror support application will have adequate lifetime and will maintain suitable flexibility at SOFIA operational temperatures.

- Estimates show that transmission of aircraft platform vibrations to the mirror cause:
  - Dynamic distortions of the mirror figure that are small compared to distortion limit guidelines
  - Mirror displacement oscillations along the telescope axis with amplitudes well below the optical budget of 5 μm
  - Mirror tilt oscillations (not yet evaluated)

- Stress in the primary mirror web has been estimated at approximately 1/4 of the allowable ULE stress under normal operating conditions

- More detailed stress analyses should be performed to more accurately establish stress levels at all expected operating conditions
structures are attached to the bearing rotor. For the telescope centerpoint structure and for the instrument frame structure, the bearing must also provide the necessary radial support. As a result, the bearing is loaded radially due to the weight of the telescope system, and the bearing is mounted in the aft cavity bulkhead wall between the pressurized cabin and the unpressurized telescope. The purpose is to isolate the three rotational degrees of freedom of the telescope system from the aircraft. The air bearing is a spherical ball located at the CG of the telescope system.
The pressure of the oil is an important parameter that affects the design of the bearing. The bearing's geometry and the oil supply pressure determine the width of the bearing and the pressure difference across the bearing. The load imposed by the oil pressure is also significant. The load and the pressure are related to each other in the sense that they affect the choice of the bearing's geometry. Providing the interface for the telescope structure requires the instrument frame structure, and the major requirements for the SOPB are summarized in the accompanying figure.
SOFIA AIR BEARING REQUIREMENTS

- TELESCOPE SYSTEM WEIGHT = 20,000 LBS
- 9.0 PSI PRESSURE DIFFERENTIAL ACROSS BULKHEAD WALL
- 135°F TEMPERATURE GRADIENT ACROSS THE BULKHEAD WALL
- + AND - 4 DEGREES MOTION IN L.O.S. AND AZIMUTH (REQUIREMENT UNDER REVIEW)
- PROVIDE 31.0 IN DIAMETER HOLE FOR OPTICAL PATH
- PROVIDE INTERFACE FOR TELESCOPE STRUCTURE AND INSTRUMENT FLANGE STRUCTURE ON BALL
- PROVIDE SEAL OR AIR SCAVENGING SYSTEM TO MINIMIZE AIR LEAKAGE INTO THE CAVITY
- MAXIMIZE BENDING STIFFNESS OF THE BALL
- MINIMIZE THE OVERALL WEIGHT OF THE DESIGN (BALL AND STATOR)
- DETERMINE PRELIMINARY REQUIREMENTS FOR THE AIR SUPPLY
- DESIGN FOR AIRCRAFT CRASH LOADS
The optics, would always be a possibility.

Using a fluid such as oil would prove difficult to seal and leak-free, with subsequent contamination of the use of air as a working fluid is desirable because it is easy to collect and is readily obtainable.

The structure and the instrumentation [Angle]

since all three axes of rotation remain orthogonal to each other.

This design is preferable over other designs (E.g., Embled) for reasons of compactness of design, truncated spherical ball (the rotor) which floats on an air film in a truncated spherical seat (stator).

The SOFIA air bearing is essentially a sealed up version of the KAV air bearing. It consists of a

Design Approach
built into the center of the bearing seat. Air is introduced into the gap through two rows of forty reed holes, one row in each half of the manifold. The reed holes are supplied with air from a manifold built into the bearing seat. Holes are drilled in the manifold to accept the manifold. The manifold is made of cast iron and is mounted directly to the bearing seat. A manifold is made of cast iron and is mounted directly to the bearing seat.

The major design features of the SOPHIA air bearing are shown in the accompanying figure. The bearing is a truncated sphere providing two flat surfaces for the attachment of the telescope.
SOFIA AIR BEARING

48.00 DIA.

.000960 GAP

23.30

31.0

7.55 7.58
It is interesting to note on the figure that the K40 air bearing (which also operates at 265 psi) has an eccentricity ratio of only 1.2.

Eccentricity ratio for the accompanying figure.

A 3.0 in. diameter hole through the bearing yet still reach the load with an acceptable operating pressure for which design data was available and is the lowest pressure that would allow the bearing to operate. The smaller diameter smaller hole, which also has a lower supply pressure, the less the bearing needs to wrap and is a simpler design. The larger of the two bearings was chosen because this is one of the few pressurized bearings with less than 3 psi higher than 265 psi was chosen because this is one of the few pressurized bearings with less than 3 psi.

The 9 psi pressure loads a 104/23 lb. axial load on the bearing. The ability of the bearing to react to these requirements is necessary to be adequate for a certain minimum size for several reasons. 1) The outside diameter of the bearing needs to be a certain minimum size (Cond).
AXIAL ECCENTRICITY RATIO VS BEARING ANGLE

\[ E_a = \frac{0.529}{P_b - P_o} \left( \sin \alpha \frac{\tan \alpha \sin \alpha}{\tan \alpha (1 - \cos \alpha)} \right)^2 \]

- \( P_b - P_o \): PRESSURE DIFFERENCE ACROSS BEARING (psia)
- \( \alpha \): BEARING ANGLE (DEGREES)
- \( E_a \): ECCENTRICITY RATIO
- \( \varepsilon_a \): OPERATING ECCENTRICITY NOMINAL GAP

MAX ACCEPTABLE \( \varepsilon_a \) (20% ACCURACY) = 0.41

\[ 36.87° (R_0/R_s = 1.25) \]

SOFIA 5/15/87

KUHNER
been made. A summary of all of the bearing parameters can be found later in this subsection.

All other bearing parameters follow in a straightforward manner after the foregoing decisions have
been made. A summary of all of the bearing parameters can be found later in this subsection.

is loaded, therefore a gap of 0.00860 in. was chosen.

Since all flow calculations are based on a centered air bearing, the gap must be chosen somewhat
smaller than the maximum allowable. This gives allowance for the change in gap size when the bearing
bore smaller than 3.0 in. diameter would be necessary and the bearing would get heavier.

For a larger air gap, the bearing would no longer be capable of reacting the axial load if the bearing were increased (so the bearing could react the axial load) a
pressure load. If the bearing were then the axial load could exceed the bearing's capacity (or exceed the axial
pressure would allow a larger air gap, but the bearing would no longer be capable of reacting the axial
load). The accompanying figure shows the maximum air gap that
may be chosen (based on the above flow considerations) for several different pressures. A lower flow supply
data, which are used to design the bearing. The accompanying figure shows the maximum air gap that
necessary to keep the flow velocity low in order to satisfy the assumptions applied to derive the design
calculations. In General, the larger the air gap, the higher the flow rate and the lower the flow velocity. It is
necessary. Once the bearing geometry and supply pressure have been chosen, the air gap must be calculated.

Concepts Details (Contd)
ORIFICE PARAMETER VS AIR GAP

\[ C = (0.006902) \left( \frac{1}{P_s} \right)^{1/2} (N_o)^{1/2} \]

- \( C \) = AIR FILM GAP
- \( P_s \) = SUPPLY PRESSURE
- \( N \) = NUMBER OF FEED HOLES
- \( d \) = ORIFICE (FEED HOLE) DIAMETER

\[ \text{MAX NOM C (INERTIA NEGLIGIBLE)} \]
\[ \text{MAX NOM C (LAMINAR FLOW)} \]
\[ \text{MAX PRACTICAL C (OPERATIONAL ECO)} \]

\( P_s = 100 \)
\( P_s = 150 \)
\( P_s = 200 \)
\( P_s = 265 \) psi

\[ \text{AIR GAP C (INCHES)} \]

\[ \text{ORIFICE PARAMETER Nd (INCHES)} \]
that this component is a strong candidate for early prototyping. It is felt
not. Building the SOPFA bearing will be a time-consuming and relatively expensive project. It is felt
ances on such a large mechanical element. All the technology exists to do this, but the tolling may
The difficulty with the SOPFA bearing is in maintaining such precise dimensional and geometric toler-

of its kind. It has ever built a spherical air bearing the size of SOPFA. In fact the KAO air bearing is still the largest
Building the SOPFA air bearing will be a task comparable to building the KAO air bearing. In the time

Feasibility Assessment
FEASIBILITY ASSESSMENT

- SIMILAR TO KAO AIR BEARING, BUT MUCH LARGER WITH TIGHTER TOLERANCES
- ADVANCES IN MACHINING TECHNOLOGY ENHANCE FEASIBILITY
- AIR BEARING OF THIS SIZE HAS NOT BEEN DEMONSTRATED
- TOOLING FOR PRECISE TOLERANCES MAY NOT EXIST
- STRONG CANDIDATE FOR EARLY PROTOTYPING
compressed air.

The accompanying chart summarizes the SOFIA air bearing parameters. The most notable items are as follows:

1. The large size of the bearing - 4.80 in. diameter.
2. The small air gap - 0.00960 in. (1/4 in.)
3. The large power requirements for the weight of the subsystem - currently 17,880 lbs., and 4) the large power requirements for the SOFIA air bearing.
SOFIA AIR BEARING SUMMARY

GEOMETRY
Bearing Diameter = 48.00 IN
Effective Length = 28.80 IN
Rotation = + and - 4 Degrees Azimuth and LOS (Unlimited in Elev.)
Nominal Air Gap = .000960 IN.

FEED HOLES
2 Rows of 40 Feed Holes (80 Holes Total) Equally Spaced @ 9 Degrees
Around Periphery, 7.584 IN. Either Side of Vertical Centerline
Feed Hole Diameter = .0410 IN.

AIR REQUIREMENTS
Flow = 40 SCFM Minimum
Pressure = 265 PSIA
Dew Point = 20°F < Minimum Ambient
Power Required to Compress Air = 6,500 Watts Minimum

BEARING STIFFNESS
Radial Stiffness = 1.481 x 10^8 LBS/IN.
Axial Stiffness = 3.286 x 10^7 LBS/IN.

OPERATING ECCENTRICITY RATIO
Radial = .140
Axial = .330

WEIGHT
Ball = 7,304 LBS
Seat = 10,560 LBS
Total Subsystem = 17,860 LBS

MATERIAL
Invar
Problem after all. Indeed, the bearing may not necessarily be made from lower or carefully designed materials. A review of the KA04116 bearing shows it has a higher thermal conductivity than the thermal spray may not be a big issue. However, the thermal gradient across the bulkhead (and bearing) may be a potential problem for SOFIA, but a small change in weight can be achieved with a goal of 12.450 lbs. The weight of the bearing is approximately estimated to be 7.800 lbs (7.400 lbs for the ball and 10.450 lbs for the seat). Clearly, this is extremely heavy. Further design work must be done to try and reduce the weight, with a goal of 12.450 lbs.

Since the bearing is an integral element in the system, however, no analytical models have yet been performed which substantiate that the bearing will maintain its figure when subjected to loads. Since the shaft gap is so small, the bearing can not be allowed to deform very much before the performance is degraded.

The most pressing concern with the SOFIA air bearing is that no detailed stress analyses have yet been performed. Analyses shows that the bearing stiffness of the bearing is sufficient for the bearing to act as a structural element in the system.
SOFIA AIR BEARING
OPEN ISSUES/MAJOR CONCERNS

- A DETAILED STRESS ANALYSIS NEEDS TO BE DONE
- WEIGHT MUST BE REDUCED
- GOOD THERMAL DESIGN IS REQUIRED, ESPECIALLY FOR ALTERNATE MATERIALS
- PROTOTYPING/TECHNOLOGY DEMONSTRATION DESIRABLE
directly recorded on the KAO. These assumptions were based on 14/5P data provided by Boeing and on data

Assumptions were also made about the magnitude of vibration the isolators experience from the

of the three translational directions. Horizontal plane also passing through the center of the air bearing. This configuration decouples the vertical plane we will be located at the center of the air bearing and that the isolators will be mounted in a structure will be located at the center of mass of the telescope in designing the vibration isolation system. It was assumed that the center of mass of the telescope weighs 30,000 lb (Telescope and Air Bearing).

The SOFIA vibration isolation system is required to attenuate all external vibrations from the telescope System Requirements and Assumptions
VIBRATION ISOLATION SYSTEM

I. REQUIREMENTS
   A. ISOLATE TELESCOPE SYSTEM FROM AIRFRAME VIBRATIONS
   B. MINIMIZE STRUCTURAL DEFLECTION
   C. SUPPORT SYSTEM WEIGHT OF 30,000 LBS

II. ASSUMPTIONS
   A. ISOLATORS MOUNTED IN PLANE OF SYSTEM MASS CENTER
      (DECOUPLED MODES OF VIBRATION IN THREE TRANSLATIONAL DIRECTIONS)
   B. AIRCRAFT RESPONSE BASED ON BOEING 747SP AND C141 DATA
Because the PSD's were random plots, a cubic spline curve fitting was performed to generate tracking. The data provided by Boeing was somewhat limited. For more accurate determination of aircraft response, additional vibration data should be taken from a 747SP. New PSD plots should be recorded over a larger frequency range in each of the three translational directions and at a location on the aircraft closer to the proposed location of the vibration isolation system (fdrp station 700).

In order to begin design of the vibration isolation system, it was necessary to determine the estimated power spectral density of the Boeing 747SP.
Frequencies that experience the lowest levels of acceleration were based on a Gaussian probability distribution. This information was used to determine the vibration based on a Gaussian probability distribution. The value resulting from the product of the PSD and complex frequency response for the structure. For a single degree of freedom system, the complex frequency response of the structure to a random excitation is the integral of the product of the PSD and complex frequency response of the structure. The mean square response of the structure to a random excitation is the integral of the product of the PSD and complex frequency response of the structure. For a single degree of freedom system, the complex frequency response of the structure to a random excitation is the integral of the product of the PSD and complex frequency response of the structure.
STRUCTURAL RESPONSE TO RANDOM VIBRATION

\[
F'(t) = \sigma \left( F(t) \right)^{1/2}
\]

where:

\( F'(t) \) = Mean Square Response of the structure to a random excitation (\( g' \))

\( F(t) \) = RMS Mean Acceleration

\( \sigma \) = Peak Response Factor (probability of \( F(t) \))

\( S(f) \) = Power Spectral Density Function (\( g'^2/\text{Hz} \))

\([H(f)H^*(f)]\) = Complex frequency response function for the structure (single degree of freedom)

where: \[
H(f) = \frac{1}{[1 + (f/f_n)^2] - i[2\xi(f/f_n)]}
\]

\[
H^*(f) = \frac{1}{[1 - (f/f_n)^2] - i[2\xi(f/f_n)]}
\]

\( f_n \) = Natural Frequency of Structure (Hz)

\( \xi \) = Damping Coefficient
Translational directions.

frequencies were not realistic and the system was designed to approximately 2.5 Hz in each of the
horizontal directions. However, due to other system requirements such as isolation, those low
frequencies were not feasible. However, due to other system requirements such as isolation, those low
directions are respectively. However, due to other system requirements such as isolation, those low
directions are respectively. However, due to other system requirements such as isolation, those low
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directions are respectively. However, due to other system requirements such as isolation, those low
directions are respectively. However, due to other system requirements such as isolation, those low
directions are respectively. However, due to other system requirements such as isolation, those low

vertical directions.

These plots show that the isolation system should have a resonant frequency below 3 Hz in the vertical

The resulting RMS accelerations were plotted versus natural frequencies for damping factors of 1%,

RMS Acceleration.
BOEING 747SP ACCELERATION DUE TO RANDOM EXCITATION

VARIABLE DAMPING

VERTICAL MOTION AT 40,000' M=0.8

LATERAL MOTION AT 40,000' M=0.8
BOEING 747SP ESTIMATED VIBRATIONAL ACCELERATIONS

<table>
<thead>
<tr>
<th></th>
<th>Ratio Tracking/Door Closed (g²/g²)</th>
<th>Area Under PSD Curve Normal Flight (g²)</th>
<th>RMS Acceleration Normal Flight (g's)</th>
<th>RMS Accelerations During Tracking (g's)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C141</strong>&lt;sup&gt;1&lt;/sup&gt; (0-100 Hz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>17</td>
<td>0.00012</td>
<td>0.011</td>
<td>0.045</td>
</tr>
<tr>
<td>Lateral</td>
<td>14</td>
<td>0.00032</td>
<td>0.018</td>
<td>0.067</td>
</tr>
<tr>
<td>Fore/Aft</td>
<td>45</td>
<td>0.00008</td>
<td>0.0089</td>
<td>0.067</td>
</tr>
<tr>
<td><strong>BOEING 747SP</strong> (0-20 Hz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>20&lt;sup&gt;4&lt;/sup&gt;</td>
<td>0.0022</td>
<td>0.047</td>
<td>0.21&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Lateral</td>
<td>15&lt;sup&gt;4&lt;/sup&gt;</td>
<td>0.0013</td>
<td>0.036</td>
<td>0.14&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
<tr>
<td>Fore/Aft</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.14&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>1</sup>Values based on actual test data taken on the KAO

<sup>4</sup>Estimated acceleration for 747SP = (normal flight accelerations) X (tracking/door closed ratio)<sup>1/2</sup>

<sup>4</sup>No fore/alt data was provided by Boeing for the 747SP in the fore/alt direction;

Lateral and fore/alt accelerations assumed equal based on C141-data

<sup>4</sup>Ratio of tracking/door closed vibrations for 747SP is assumed equivalent to that for the C141
The results shown are for a 2.5 Hz system plotted over a frequency range of 0-100 Hz for the vertical accelerations.

\[ t = \text{Damper Factor} \]

\[ \text{Design Frequency/ } \frac{\text{System natural frequency}}{\text{Transmissibility}} = \left(1 + \left(\frac{f}{f_n}\right)^2\right) \]

\[ f_n = \text{Natural frequency of the isolation system} \]

\[ f_{V_{20}} = 0.0032/20 = 0.016 \text{ Hz} \]

\[ f_{L_{40}} = 0.0013/20 = 0.0065 \text{ Hz} \]

For the 4135 PSD curve, the average level of white noise was determined by dividing the area under the PSD curve by the RMS value. The average level of white noise of 0.2/Hz. The transmitted accelerations through the isolators were calculated by the following equation:

\[ \text{Transmitted Accelerations} = \frac{1/2 \text{ PSD}}{1/2} \]
TRANSMITTED ACCELERATIONS FOR EQUIVALENT WHITE NOISE PSD'S

LATERAL AND FORE/AFT AXES

\[ f_n = 2.5 \]
PSD EQUIVALENT WHITE NOISE = 65 \( \mu \text{g}^2/\text{Hz} \)

VERTICAL AXIS

\[ f_n = 2.5 \text{ Hz} \]
PSD EQUIVALENT WHITE NOISE = 110 \( \mu \text{g}^2/\text{Hz} \)
The total stiffness in each direction is a combination of the stiffness for the isolators, internal springs and air springs. The total stiffness is calculated as the sum of the stiffness for each of these components. The natural frequency of the system is determined by the stiffness of the isolators and springs and the mass of the system. The isolators provide high-frequency vibration isolation and reduce the effect of external vibrations. The proposed isolation system will consist of four pneumatic isolators, each located in a plane parallel to the floor and elevated above the floor level.
VIBRATION ISOLATION SYSTEM
PROPOSED SYSTEM

A. FOUR SEMI-ACTIVE PNEUMATIC ISOLATORS
   (1) MINIMUM OF THREE ISOLATORS FOR SYSTEM STABILITY
   (2) PNEUMATIC ISOLATORS PROVIDE LOWER SYSTEM NATURAL FREQUENCY
   (3) ISOLATORS INCORPORATE RELAXATION DAMPING PRINCIPLES
   (4) ISOLATORS ARE ACTIVE IN AXIAL DIRECTION
   (5) AXIAL STIFFNESS - 5,000 LB/IN.  RADIAL STIFFNESS - 1250 LB/IN.

B. FOUR PASSIVE PNEUMATIC ISOLATORS - ISOLATE FORE/AFT VIBRATIONS
   AXIAL STIFFNESS - 3750 LB/IN.  RADIAL STIFFNESS - 1875 LB/IN

C. INTERNAL SNUBBERS - ISOLATE VIBRATIONS WHEN SYSTEM IS LOCKED (SYSTEM
   LOCKS WHEN LOADS EXCEED 0.25g's AND DURING TAKE-OFF AND LANDING)
   AXIAL STIFFNESS - 46,140 LB/IN.  RADIAL STIFFNESS - 23,070 LB/IN.

D. EXTERNAL SNUBBERS - PREVENT METAL TO METAL CONTACT BETWEEN BULKHEAD
   AND STATOR RING ASSEMBLY DURING EXTREME LOADS (DESIGNED FOR CRASH LOADS)
Therefore, the total maximum deflection in any direction will be less than 1 in.

\[ \frac{K}{D} = \frac{d}{E} \]

The isolation and the maximum deflection (d) in that mode as follows:

The maximum deflection (d) of the system for each mode of operation is based on the total stiffness of the isolators and internal snubbers.

When the system weight (m) is 30,000 lb, the stiffness will be provided by the isolators, air springs:

\[ K = \frac{m}{(2\pi f_n)^2} \]

The system stiffness (K) is determined from the natural frequency (fn) of the system.
# Proposed Vibration Isolation System

**Diagram:**
- **Cabin Side Aft Bulkhead**
- **Approximate Location of Isolators 4 PL.**

### Table:

<table>
<thead>
<tr>
<th></th>
<th>Natural Frequency (Hz)</th>
<th>Stiffness (Lb/ln)</th>
<th>Maximum Acceleration (g's)</th>
<th>Deflection (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tracking</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>2.48</td>
<td>19,000</td>
<td>0.25</td>
<td>0.375</td>
</tr>
<tr>
<td>Lateral</td>
<td>2.48</td>
<td>19,000</td>
<td>0.25</td>
<td>0.375</td>
</tr>
<tr>
<td>Fore/Alt</td>
<td>2.54</td>
<td>18,700</td>
<td>0.25</td>
<td>0.375</td>
</tr>
<tr>
<td><strong>Locked System</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>6.9</td>
<td>146,000</td>
<td>+3.04</td>
<td>0.625</td>
</tr>
<tr>
<td>Lateral</td>
<td>6.9</td>
<td>146,000</td>
<td>-1.04</td>
<td>0.20</td>
</tr>
<tr>
<td>Fore/Alt</td>
<td>5.9</td>
<td>107,000</td>
<td>0.63</td>
<td>0.30</td>
</tr>
<tr>
<td><strong>Crash Limit Loads</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>6.9</td>
<td>146,000</td>
<td>+4.5</td>
<td>0.93</td>
</tr>
<tr>
<td>Lateral</td>
<td>6.9</td>
<td>146,000</td>
<td>-2.0</td>
<td>0.51</td>
</tr>
<tr>
<td>Fore/Alt</td>
<td>5.9</td>
<td>107,000</td>
<td>+3.5(^a)</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-1.5</td>
<td>0.42</td>
</tr>
</tbody>
</table>

\(^a\) Stiffness and natural frequency determined by pneumatic isolators, air springs and internal snubbers
\(^b\) Stiffness and natural frequency determined by air springs and internal snubbers
\(^c\) Maximum forward crash load is 6 g's. External snubbers minimize motion beyond 1' deflection and 3.5 g's (forward direction)

155
Within the surge tank, additional control of the system stiffness and natural frequency is available by varying the air pressure based on actual accent response.

By using a variable orifice in the design an optimum orifice size can be determined upon installation volume of both the surge tank and the load carrying chamber.

For a larger orifice the restrictions are lowered and the system is determined by the pressure and volume in the load carrying chamber.

The system characteristics (i.e., natural frequency and stiffness) will be determined by the pressure and pronounced variations in resonant frequency. When the orifice is small, flow is highly restricted and resonant variations in the orifice can result in frequency for which resonant response is a minimum. Small variations in the orifice can result in transmitted to the telescope.

This controls the magnitude of vibration as well as the stiffness and natural frequency of the system. The size of the orifice will determine the amount of system damping and a control flow restriction. The size of the orifice will determine the amount of system damping which acts compressed air flowing from a surge tank into a load carrying chamber through an orifice which acts to

Damped Pneumatic System
DAMPED PNEUMATIC ISOLATORS

* ORIFICE SIZE DETERMINES DAMPING

SMALL ORIFICE - HIGH RESTRICTION

\[ C = \infty \quad K_{\infty} = 2nPA^2 / V_c = K_{LCC} \]

where:  
- \( C \) = DAMPING CONSTANT  
- \( K \) = ISOLATOR STIFFNESS  
- \( n = 1.4 \) FOR COMPRESSED AIR  
- \( P \) = PRESSURE IN CYLINDER  
- \( V_c \) = LOAD CARRYING CHAMBER VOLUME  
- \( A \) = PISTON AREA

LARGE ORIFICE - LOW RESTRICTION

\[ C = 0 \quad K_0 = 2nPA^2 / (V_c + V_t) = \frac{(K_{LCC})(K_{ST})}{K_{LCC} + K_{(LCC+ST)}} \]

where:  
- \( V_t \) = SURGE TANK VOLUME
This design is feasible; however, additional possibilities should be investigated.

Control for resetting.

For sudden impacts above 0.25 G's, the piston will lock back into the catching mechanism. To release the piston, insert a tool above the catching mechanism at which point the mechanism closes.

A possible design for the catching mechanism on 60PIA is one similar to that on the KAO. The piston
A final tradeoff that should be performed in greater depth is the "soft system vs. stiff system" approach. The "soft system" approach is more flexible and can accommodate changes in the system. The "stiff system" approach is more rigid and less forgiving of changes. The choice between the two approaches depends on the specific requirements of the system and the environment in which it will operate.

Any follow-on effort.

Concerns/Issues:

Several areas requiring further analysis and tradeoff activity still exist for the SOFIA vibration isolation systems. Although basic feasibility of a candidate concept has been demonstrated, in the area of structural response, 747SP PSDs should be measured at a preliminary stage with additional information collected. For the unmodified 747SP, consideration is needed to address modifications for vibration levels. For the modified 747SP (747SP), measured data is somewhat expected, as one would expect lower fore-elastic response. The Boeing provided data is somewhat suspect, as well.

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CONCERNS/RISKS

A. AIRCRAFT RESPONSE

(1) 747SP DATA PROVIDED BY BOEING WERE FOR BODY STATION 310 OF THE AIRCRAFT WHEREAS THE TELESCOPE WILL BE MOUNTED AT BODY STATION 700

(2) BOEING PSD'S PROVIDED VIBRATION DATA IN THE LATERAL AND VERTICAL DIRECTIONS ONLY

(3) BOEING PSD'S PRESENTED LEVELS OF VIBRATION FOR THE 747SP WHICH WERE HIGHER THAN THOSE FOR THE C141; MASS TO WING AREA RATIOS WOULD SUGGEST OTHERWISE

(4) EFFECTS OF THE OPEN CAVITY ARE BASED ON C141 DATA ONLY

B. POTENTIAL MASS CENTER OFFSET WOULD RESULT IN COUPLED MODES OF VIBRATION AS WELL AS ADDITIONAL TORQUES ACTING ON THE ISOLATION SYSTEM

C. TORQUERS PRODUCE REACTION FORCES THROUGH VIBRATION ISOLATION SYSTEM

D. TRADE OFF BETWEEN MINIMIZING RESPONSE TO AIRCRAFT VIBRATION, SOFT SYSTEM BEING MORE ADVANTAGEOUS, TO MINIMIZING RESPONSE TO AERO LOADS WHERE A STIFF SYSTEM WOULD BE BETTER
required along with a maximum acquisition time of 30 seconds.

Mapping capability with various motion patterns is required as well, as capability for storage of up to 12 accumulations, or better.

is specified. Capability up to 2x accumulations per second in any combination of motions in the three axes of rotation is required. Setting time (1% or less of amplitude) of 2 seconds or less for a 5 accumulation nod is preferred. Setting time (1% or less of amplitude) of 1D accumulations is required, with a setting time (1% or less of amplitude) of 5D accumulations is required. Setting time (1% or less of amplitude) of 10D accumulations is required.

The telescope elevation axis is required to have a commanded settleable range of travel between and 0.5 arcseconds/second. The telescope azimuth axis is required to have a commanded settleable range of travel between and 0.5 arcseconds/second. The telescope cross-axis is required to have a commanded settleable range of travel between and 0.5 arcseconds/second.

The SOFIA telescope system, with inertial stabilization and a three-axis controlled system with inertial stabilization and cross-axis, will be able to track targets within the field of view of the primary mirror. The cross-axis is required to have a commanded settleable range of travel between and 0.5 arcseconds/second. The SOFIA telescope system will be able to track targets within the field of view of the primary mirror. The cross-axis is required to have a commanded settleable range of travel between and 0.5 arcseconds/second.
GENERAL POINTING SYSTEM REQUIREMENTS

- **3 DEGREES OF FREEDOM**
  - ELEV: 20° TO 60° COARSE RANGE (UNVIGNETTED)
  - ELEV, AZIM, LOS ± 4° DYNAMIC RANGES

- **3-AXIS STABILIZATION**

- **AZIMUTH AND ELEVATION TRACKING ON AXIS**
  - AZIM, ELEV, AND LOS TRACKING OFF AXIS

- **TRACKING ERROR SIGNALS DERIVED FROM ANY OF THREE CAMERAS**

- **TRACKING SAMPLING RATE ≥ 10 Hz**

- **DRIFT RATE ≤ 0.5 ARCSEC/SEC WITH TRACKER LOOPS OPEN**

- **TELESCOPE NODDING**
  - 0 TO 20 ARCMIN IN ANY DIRECTION
  - SETTLING TIME (FOR 5 ARCMIN NOD) 2 SEC
  - ACCURACY 1% OF AMPLITUDE (OR 0.15 ARCSEC)
  - $M_v = 13$ OR BRIGHTER

- **SLEWING**
  - 0 TO 24 ARCMIN/SEC IN ANY DIRECTION

- **AUTOMATED MAPPING USING CIRCULAR, SPIRAL, AND RASTER PATTERNS**

- **STORED TARGET LOCATION FOR NOD FUNCTION (UP TO 4) WITH AUTOMATED SCHEDULES OR OPERATOR INITIATED TARGET SELECTION**

- **DEAD RECKONING ACCURACY BETTER THAN 15 ARCMIN**

- **ACQUISITION TIME ≤ 30 SECONDS AFTER ESTABLISHMENT OF HEADING AND COARSE ELEVATION**
Much progress is currently being made in the CCD camera arena. It appears that a reassessment of the new sensor units.

The requirements here will be made in the near future when more is known about the capabilities of the

...of the other two camera systems (the Tracker and Acquisition) is needed.

Further study is necessary to determine if acceptable orbital pointing requirements can be met when either

...the orbital plane and elevation. Orbital pointing stability of 1.0 arcsecond is required when utilizing the focal plane

Tracker. In addition, meaningful gimbal motion is required to provide up to 35 arcminutes of motion in azimuth

Tracker be, in addition, meaningful gimbal motion is required to provide up to 35 arcminutes of motion in azimuth

Orbital tracking requirements are that the system be able to electro-optically acquire the guide target from the science target anywhere within the respective FOV of the tracking units and that the guide target upon detection can be

pointed at in the 15 arcsecond RMS stability requirement with reasonable accuracy. Further could be

...acquisition unit at a slightly relaxed requirement for detectable targets of 1.1 visual magnitude for

...minimum +12 and brighter with FOV of 6 and 30 arcminutes respectively. To aid in the

...magnitude +12 and brighter with FOV of 6 and 30 arcminutes respectively. To aid in the

...traces to be used in the focal plane detector. The focal plane detector is derived from the Focal Plane System of two stars in the field-of-view (FOV). The Focal

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University of California Riverside - Center for Applied Isotopic Microscopy
TRACKING AND ACQUISITION REQUIREMENTS

- FOCAL PLANE TRACKER
  - 2-STAR GUIDANCE CAPABILITY $M_v = +13$ AND BRIGHTER
  - FOV = 8 ARCMIN
  - ELECTRONIC OFFSET IN AZIM AND ELEV = ± 4 ARCMIN
  - POINTING STABILITY 0.15 ARCSEC RMS (ON AXIS)
  - OFFSET POINTING STABILITY 1.0 ARCSEC RMS

- FINE TRACKER
  - 2-STAR GUIDANCE CAPABILITY $M_v = +13$ AND BRIGHTER
  - FOV = 30 ARCMIN
  - GIMBALLED MECHANICAL OFFSET
    - 30 ARCMIN in AZ AND ELEV
  - POINTING ACCURACY ± 10 ARCSEC (ON AXIS)
  - OFFSET POINTING TBD

- ACQUISITION CAMERA
  - 2-STAR GUIDANCE CAPABILITY
  - REMOTE ZOOMING
  - FOV ~ $9^\circ \times 12^\circ$ FOR $M_v = +11$ AND BRIGHTER
  - FOV ~ $2.5^\circ \times 3.5^\circ$ FOR $M_v = +13$ AND BRIGHTER
  - ELECTRONIC OFFSET IN AZ AND EL ± 1/2 FOV
  - POINTING ACCURACY 15 ARCSEC RMS (ON AXIS)
  - OFFSET POINTING STABILITY TBD
compensation of small mirror attitude correction techniques must be necessary.

Inertial stabilization when rate integration errors for remote control will be the fourth level of control.

rotation during operation of extended objects the issue is present under review.

The dynamic error range of altitude correction is highly dependent on the expected error of the attitude system with errors of -0.1 degree after the expected modulation of the LGS reference could be kept with about +0.1 degree after the expected modulation of the LGS reference could be kept.

The dynamic error range of altitude correction is highly dependent on the expected error of the attitude system with errors of -0.1 degree after the expected modulation of the LGS reference could be kept with about +0.1 degree after the expected modulation of the LGS reference could be kept.
POINTING AND STABILIZATION CONTROL LEVELS

- AIRCRAFT
- VIBRATION ISOLATION SYSTEM
- AIR BEARING
- GYRO STABILIZATION CONTROL SYSTEM
- VIDEO TRACKING CONTROL SYSTEM
are experienced to be incorporated. Technologies not requiring the star tracker in use to determine field rotation, and star-field recognition.

Automatic periodic telescope focus compensation, automatic LOS axis null compensation (using other spacecraft), and the experiment with the proper signals at the proper times. Special functions such as >>>spontaneously programmed to provide the pointing system, the console monitors, the data logging system, the control consoles and the experiment computer are stored and edited upon system command generator and data handling. Information from the various system sensors, data system command generator and data handler. Information from the various system sensors, data system. Central to the system is the digital computer. This unit is considered to basically be a system. The control system block diagram shows the interaction between various units within the telescope.
Individual tracking or stabilization loops.

Supervisory computer would act as a higher-level or automation command generator. For any of the

joysticks, providing the means for real-time operator control of the telescope's attitude, the

depending on whether the cross or offset tracking mode of operation is being used. Whereas, the

output signals depending on the availability of two or more targets in the given field of view, and

any of the three channels, the tracker electronics system would provide either two or three axes

channels, as mentioned earlier, to be utilized appropriately in the various modes of operation. Using

orthogonal axes or baseline control, each axis would be associated with its own specialized electronics

three-axis pointing system diagram portrays the envisioned configuration consisting of these

Three-axis pointing system
The telescopic system Moment of Inertia (MOI) matrix shown on the opposite page indicates

Very high at about 24 percent. The coupling in the X-Y and X-Z axes are reasonable, the coupling in the Y-Z axes combination is

associated with the lowest and the line-of-sight axis with the highest MOI and although cross axes

several notable points. The MOI range between 42 million and 137 million lb-in., the elevation axis is
## Telescope Structure Moment of Inertia

<table>
<thead>
<tr>
<th>MASS AXIS</th>
<th>EL</th>
<th>LOS</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>1.265 x 10^8</td>
<td>4.576 x 10^5</td>
<td>3.846 x 10^5</td>
</tr>
<tr>
<td>Y</td>
<td>4.232 x 10^7</td>
<td>4.004 x 10^7</td>
<td>-1.004 x 10^7</td>
</tr>
<tr>
<td>SYM</td>
<td>1.374 x 10^8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All values are in units of lb-in²
expected perturbations are estimated to be relatively small and may be compensated for by the system. The other four estimates show up to 2000 IDT of peak torque being imposed on the telescope system. The other four isolation system, aerodynamic loadings pose the largest threat to the pointing system in that current isolation system, reaching the telescope will clearly be dependent on the characteristics of the telescope's performance. Preliminary studies show that we may expect about 0.1-0.26 RMS of vibration input from the aircraft to the base of the isolation system. The magnitude and frequency content undesirable input. Preliminary studies show that we may expect about 0.1-0.26 RMS of vibration input.

Dependent significantly on the effectiveness of the active damping in the baseline design to attenuate the disturbances to the system. Current requirements call for active control to be limited to 0.5° of vibration, with an additional requirement for aeroelastic loadings being the most significant. Seven specific perturbations to the pointing and control system are identified, with active control measures
POINTING SYSTEM PERTURBATIONS

- AIRCRAFT ATTITUDE EXCURSIONS
- AIRCRAFT VIBRATION
- OPEN PORT AERODYNAMIC LOADING
- THERMALLY INDUCED MISALIGNMENTS
- TRACKER NOISE AND QUANTIZATION ERROR
- GYRO NOISE
- ELECTRONIC NOISE AND DRIFT
tracking budget

The tracking system error budget, as depicted, uses 0.15 arcseconds RMS as the total stability error.

This assumes that focal plane tracking, when a sensor sharing the main optics focal plane, is the mode of operation. For which this budget applies. Note here that the bulk of the total budget is allocated to aerodynamic loading, structural vibration and uncommanded excursions.
TRACKING SYSTEM ERROR BUDGET

Focal Plane
Tracking Error
0.15 arcsec RMS

A/C Excursions
0.06 arcsec RMS

A/C Vibration
0.08 arcsec RMS

Thermal Shift
0.03 arcsec RMS

Aerodynamic
Loading
0.1 arcsec RMS

Sensor and
Electronic Noise
0.03 arcsec RMS
ACQUISITION CAMERA DISPLAY

TIME  LONGITUDE  LATITUDE  HEADING

12:18:01  140:30.2  30:40.1  170

ENHANCED DISPLAY OF TRACKER FOV

OPTIONAL DISPLAY OF ESTIMATED STAR FIELD

DISPLAY OF ACTUAL STAR FIELD

AZ = 1.2  EL = 41.3  LOS = +0.2

LOCATION OF TELESCOPE WITHIN POINTING RANGE

STATUS INDICATORS

TELESCOPE ATTITUDE
Telerescope Tracker Display

As similarly described for the Acquisition Camera Display, this chart illustrates some concepts which
The transfer function block diagram illustrates how a typical single-axis of the three-axis compensator dipole were systematically selected to provide acceptable simulated responses.
TRANSFER FUNCTION REPRESENTATION OF OVERALL SYSTEM

**Tracker Compensation**
\[ \frac{K_d (S + Z \omega)}{K_T (S + p_T)} \]

**Tracker Dynamics**
\[ \frac{K_T}{S + 6.28} \]

**RIG Closed-Loop Transfer Function**
\[ \frac{D_c S^3 + d_3 S^2 + d_4 S + d_5}{S^5 + d_1 S^4 + d_2 S^3 + d_3 S^2 + d_4 S + d_5} \]
necessary and appear achievable. Note that a system bandwidth of something more than 10 Hz is
necessary and achievable, respectively. The frequency response of the system rate loop as conceptually designed:

The resulting two plots show the frequency response magnitude and phase.
FREQUENCY RESPONSE OF RIG LOOP, CONTINUOUS MODEL (Bandwidth = 13.84 Hz)

(a) GAIN VERSUS FREQUENCY

(b) PHASE VERSUS FREQUENCY
nodes easily met the required 2 seconds or less, as shown. The rise times obtained for 5 arcminute telescope and compensation pole-zero locations were made. The rise times obtained for I arcmin telescope

The pointing control system with its tacker loop closed around a tuned rate loop (as depicted by the

Tracking System Step Response
STEP RESPONSE OF TRACKER LOOP (10 Hz SAMPLING FREQUENCY)
Thereby minimizing both the need for larger special jigs and difficult maintenance procedures.

permanente magnet motors provide roughly 3600 pounds of force for the 650 lb-ft RMS units would be reduced.

taken, a side benefit would be that the large static friction forces inherently associated with these

motor's design is the multiple motors per axis approach is

through large torques or course, is to design the system using multiple smaller motors per axis.

Although obviously complicated the mechanical design of the multiple motors per axis approach is

throughout 2400 lbf-ft and operating at radii of 3 to 4 feet. A possible alternative to the requirement for

range of 2400 lbf-ft and operating at radii of 3 to 4 feet. A possible alternative to the requirement for

were basic extensions of the ones being used by the KVO telescope, with peak torque ratings in the

responded with a fair amount of confidence that they could build segmented spherical motors, which

been constructed and geared about the feasibility of motors of this size and configuration.

Two of them

endurance times fell by the telescope indicate the need for torque motors with RMS ratings of

extensions in design of the segmented spherical permanent magnet motors. Preliminary estimates of

mutually to be outgrown by the torque motors used in the current airborne observatories. Evaluations are

following the Kupfer-Ahrometer Observatories (KVO) basic concept, the system prime movers tend

With the baseline telescope design utilizing a monoball or bearing for primary support,

Torque Motor Concept
TORQUE MOTORS CONCEPT

- MAGNETIC
- SEGMENTED SPHERICAL
- ESTIMATED REQUIRED RATED TORQUE = 650 LB-FT
- ESTIMATED REQUIRED PEAK TORQUE = 1950 LB-FT
- MOUNTED AT 3-4 FEET RADII
- EXTENSION OF CURRENT KAO DESIGN
Results of conceptual studies show that cameras for the three Tracking and Acquisition (T&A) systems could be simple extensions of those in use on the KAO. New ISIT cameras with proper front-end optics would be the design choice at this point in time. Systems using CCD arrays are, however, beginning to show very promising signs. Usable error signals for pointing corrections have been obtained from CCD units working on very dim targets. Array uniformity, chip availability and long required integration times for faint objects, however, are some of the areas of concern being closely followed for developing improvements. Currently available on the market are relatively precise and fast video tracking electronic "black boxes". Significant efforts will be made to incorporate these off-the-shelf units or their future extensions to ease the perpetual need for increasing numbers of technical specialists and stringent documentation controls for one-of-a-kind systems.
TRACKER AND ACQUISITION SYSTEM CAMERAS OPTIONS

- EXTRAPOLATIONS OF CURRENT KAO OPTICS
- ISIT TELEVISION CAMERAS
- CCD CAMERAS
- OFF-THE-SHELF TELEVISION TARGET TRACKERS
Several candidate gyroscopes were investigated for their applicability to the inertially referenced stabilization control loops on the SOFIA telescope system. Of these, three are listed in the chart and compared to the Honeywell GG334A, which is the model originally selected for the KAO system and considered to be the Honeywell GG334A, an improvement over the SOFIA telescope system. Both the Telephone 2D-5 and the Northerp CGG-5 and the Honeywell GG334A in these two categories. Both the Telephone 2D-5 and the Northerp CGG-5 come reasonably close to the specification for ADRR and Random Drift. The Northerp CGG-5 comes reasonably close to the specification for ADRR and Random Drift. Although the ADRR (bias drift) can be matched or better by any of the other types, only the Telephone 2D-5 has equal or better

Sofia Telescope
## STABILIZATION LOOP GYROS

<table>
<thead>
<tr>
<th></th>
<th>Honeywell GG334A</th>
<th>Honeywell GG1111</th>
<th>Northrop GIG6</th>
<th>Honeywell GG8200</th>
<th>Northrop GIG6G</th>
<th>Tekdyne SDG-5*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Gas Bearing Rate Integrating</td>
<td>Ball Bearing Rate Integrating</td>
<td>Ball Bearing Rate Integrating</td>
<td>Gas Bearing Rate Integrating</td>
<td>Gas Bearing Rate Integrating</td>
<td>Dry Tuned Bearing Rate</td>
</tr>
<tr>
<td><strong>Deg. of Freedom</strong></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Ang. Momentum</strong></td>
<td>$2 \times 5^5$</td>
<td>$2.5 \times 10^4$</td>
<td>$3.2 \times 10^4$</td>
<td>$3.2 \times 10^4$</td>
<td>$8 \times 10^4$</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td><strong>O.A. Freedom</strong></td>
<td>$\pm 0.5$</td>
<td>$\pm 0.25$</td>
<td>$\pm 14.0$</td>
<td>$\pm 14.0$</td>
<td>$\pm 0.5$</td>
<td>—</td>
</tr>
<tr>
<td><strong>Gryo Gain</strong></td>
<td>0.8</td>
<td>0.84</td>
<td>0.7</td>
<td>0.7</td>
<td>$\pm 0.27$</td>
<td>—</td>
</tr>
<tr>
<td><strong>Torque Max Rate</strong></td>
<td>86</td>
<td>90</td>
<td>115</td>
<td>115</td>
<td>50</td>
<td>400</td>
</tr>
<tr>
<td><strong>AIDR (Deg/Hr)</strong></td>
<td>$\pm 0.5$</td>
<td>$\pm 0.5$</td>
<td>$\pm 15.0$</td>
<td>$\pm 15.0$</td>
<td>$\pm 1.5$</td>
<td>$\pm 2.0$</td>
</tr>
<tr>
<td><strong>ASDR (Deg/Hr/g)</strong></td>
<td>$\pm 1.0$</td>
<td>$\pm 15.0$</td>
<td>$\pm 14.2$</td>
<td>$\pm 10.0$</td>
<td>$\pm 2.0$</td>
<td>$\pm 1.0$</td>
</tr>
<tr>
<td><strong>Random Drift</strong></td>
<td>$\pm 0.002$</td>
<td>$\pm 0.15$</td>
<td>—</td>
<td>$\pm 0.1$</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.001$</td>
</tr>
<tr>
<td><strong>Supp. Electronics</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Lead Time</strong></td>
<td>—</td>
<td>3</td>
<td>3</td>
<td>6-12</td>
<td>6-12</td>
<td>12-24</td>
</tr>
</tbody>
</table>

*SDG-5 Gyro assemblies use supporting electronics to provide integration.*
Elements of the system. Auxiliary operator's console is integrated to simplify the need for front panel space for each of these.

For operator manipulation and monitoring of parameters within these subsystems from a main or various subsystems external to the total telescope electrical and control system. The requirements of the accompanying tabulation is generated primarily to list, for informational purposes, most of the control and monitoring systems.
## Control and Monitoring Systems

<table>
<thead>
<tr>
<th>Control System Type</th>
<th>Front Panel Controls</th>
<th>Front Panel Disp/Indic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boundary Layer Fence Control</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Coarse Telescope Elev Control</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Aperture Door</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Aperture Shield</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Pressure Window Wheel</td>
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<td>X</td>
</tr>
<tr>
<td>Telescope Auto Balance</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Telescope System Activ/Shutdown</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Telescope Stabilization</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Target Acq &amp; Tracking</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Chopper Drive</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Secondary Mirror Focus</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Mech Offset Pointing</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Telescope Auto Centering</td>
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<td>X</td>
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<tr>
<td>Telescope Caging</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Air Bearing</td>
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<td>X</td>
</tr>
<tr>
<td>Telescope Attitude Readout</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Telescope System Fault Annunc</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>System Intercom</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Video Distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimenter Power Dist</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum System</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibration Isol System</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
It has been shown in the telescopic structural design section (4.2) of this phase A, that in addition to the 1-

4-196
PACS CONCERNS/RISKS

- STRUCTURAL MODES
- AERODYNAMIC LOADING
- A/C VIBRATIONS
- AIR BEARING FRICTION
- TORQUE MOTOR OPTIONS
- NEED FOR IMC
To enable rough costing to be calculated, this study is intended only to outline system considerations, develop a conceptual architecture for an efficient, reliable, and expandable system, and provide sufficient supplemental detail.

SCOPE

This section provides a conceptual design for the Data Management, Acquisition, and Communication Subsystems network technologies. As the SOFA DNNAC System is not subject to questions of functional blocks of the KAO, including planned upgrades and incorporate advances in modern communications. The system design is to incorporate major command signals for further supervisory regulation. The system design is to incorporate major hardware and software needed for acquisition the various subsystems, sensor data, process, route, and store data, including the NOGO command promp for go/no-go command.
SCOPE AND GUIDELINES

SCOPE

- DETERMINE SYSTEM REQUIREMENTS
- DEVELOP CONCEPTUAL SYSTEM ARCHITECTURE
- PROVIDE INPUTS FOR COST ANALYSIS

DESIGN GUIDELINES

- USE KAO AS SYSTEM MODEL
- INCORPORATE PLANNED KAO UPGRADES/MODERN TECHNOLOGY
- INPUT REQUIREMENTS FROM:

  KAO SUPPORT CONTRACTORS, KAO OPERATIONS STAFF, AND SOFIA STAFF
increase efficiency in configuring the system for the user.

The design concept for the SOPFA Data Management, acquisition, and Communications System is based on the KAO system, including planned upgrades. Major Requirements for the system include high

Majur Requirements

The communication requirements include direct subsystem-to-subsystem data transfer via a standard protocol is required, to keep the real-time up to date and allow for expansion of capability as needed.

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The communication requirements include direct subsystem-to-subsystem data transfer via a standard protocol is required, to keep the real-time up to date and allow for expansion of capability as needed.
MAJOR REQUIREMENTS

- RELIABILITY
  - HIGH MEAN TIME BETWEEN FAILURES
  - HIGH NOISE IMMUNITY

- REDUNDANCY
  - BACKUP DATA CPU FULLY AVAILABLE FOR IMMEDIATE SWITCHOVER
  - STAND-ALONE AND NETWORK OPERATION

- MODIFIABILITY
  - STANDARDIZATION OF HARDWARE AND COMMUNICATION PROTOCOLS SIMPLIFIES SYSTEM MODIFICATIONS AND SYSTEM EXPANSIONS
  - NETWORK CONCEPT SIMPLIFIES BRINGING UP SYSTEM IN PHASES

- DATA COMMUNICATIONS
  - NETWORK CONCEPT ALLOWS DIRECT SUBSYSTEM-TO-SUBSYSTEM DATA COMMUNICATIONS
  - LINK TO GROUND STATION INCREASES EFFICIENCY OF USER CONFIGURATION
  - IMPLEMENTATION OF AN INDUSTRY STANDARD COMMUNICATION NETWORK
  - NETWORK MANAGER AND TEST WORK STATION PROVIDED FOR NETWORK CONFIGURING AND SYSTEM MAINTENANCE
The following is a brief decription of each of the subsystems:

1. Oscillating Secondary Mirror Subsystem - This subsystem provides focusing position angle of the telescope.

2. Family Upper Child Subsystem - This subsystem moves the focal plane camera to enhance the chop, offset, amplitude and frequency control to the telescope secondary mirror.

3. Focal Plane Camera - It is used in conjunction with the Star Tracker subsystem.

4. Telescope Inertial Pointing Subsystem - This subsystem monitors the position of the telescope and articulation position, speed, heading, with speed and angle, and global position data to position the secondary.
18. Miscellaneous Peripherals Equipment - This subsystem is a collection of peripheral equipment. It includes the printer, plotter, and MY receiver.

Video Distribution Subsystem - This subsystem provides for the distribution and display of video signals. Channels, which allow for longer distances between stations and multiple broadcast CATV-like technology, whose signals are distributed to specific locations. The broadcast and video channels are broadcast to the handheld receivers using broadcast CATV-like technology. An intercom system that consists of a "token bus" approach, the MAC/LAN architecture is a hierarchical structure that can be used to broadcast automation protocols. The protocol is ideal for real-time applications and uses the MAN, between subsystems via a single coax cable at 0.5 megabits per second using standard MAN, MAN. Broadband Local Area Network (LAN) - This subsystem provides a standard and transport network, initial terrestrial differential between the telescope and the observing attitude.

15. CCTV Pre-Code Subsystem - This subsystem provides pre-code to the telescope to reduce the initial terrestrial differential between the telescope and the observing attitude.

Remote P.I. Workstation - This subsystem provides the investigator team with a remote workstation to do offline editing, analyze, etc.

Network Manager and Test Workstation - This subsystem provides the Mission Manager with access to log generation software, light planning and facility monitoring, and control.

Mission Manager Workstation - This subsystem provides real-time video enhancement.

Video Signal Processor Subsystem - This subsystem processes real-time video enhancement.

10. Backup Data CPU Subsystem - This subsystem provides a full backup to the primary experimental data and performs utility functions.

Data and Experimental Data Subsystem - This subsystem collects and records data from the primary experiment. It processes experimental data and supports the principal investigator in the experiment.

Housekeeping and Data Acquisition Subsystem - This subsystem collects and records housekeeping data.
SEVEN FUNCTIONAL BLOCKS

1. LAN
2. PROCESSOR
3. CONTROL PANEL
4. CONTROL INTERFACE
5. MOTORS, TRANSDUCERS, CONTROLLERS, ETC.
6. FIRMWARE/SOFTWARE
7. MASS STORAGE

(POSSIBLE MANUAL BACKUP)
This chart outlines the major elements of each of the subsystems. A bulleted item indicates the element is a part of the design and cost responsibility of the DMAC system. An open circle indicates that the element is outside the area of this system.

1. **Ground Base System** - This system provides general ground base support for SOPRA, i.e., to develop new software, reduce data from past flights, and develop flight plans.

20. **Ground Base System** - This system provides general ground base support for SOPRA, i.e., to...

19. **Ground Base System** - This link allows for communication between the ground base system...

[End of document]
# SOFIA

## CONCEPT DETAILS

### SOFIA Table

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>Miscellaneous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillating Secondary Mirror Subsystem</td>
<td>●</td>
<td></td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Facility Offset Dither Subsystem</td>
<td>●</td>
<td></td>
<td>●</td>
<td></td>
<td>●</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Star Tracker Subsystem</td>
<td>●</td>
<td></td>
<td>●</td>
<td></td>
<td>●</td>
<td></td>
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<tr>
<td>Telescope Inertial Pointing Subsystem</td>
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<td></td>
<td>●</td>
<td></td>
<td>●</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Vibration and Noise Isolation Subsystem</td>
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<td></td>
<td>●</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Telescope System Support Subsystem</td>
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<td></td>
<td>●</td>
<td></td>
<td>●</td>
<td></td>
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<td></td>
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<tr>
<td>Principal Investigator Subsystem</td>
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<td></td>
<td>●</td>
<td></td>
<td>●</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Housekeeping &amp; Data Acquisition Subsystem</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
<td>●</td>
<td>○</td>
<td>●</td>
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<td>Data CPU Subsystem</td>
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<td>●</td>
<td>●</td>
<td></td>
<td>●</td>
<td>○</td>
<td>●</td>
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</tr>
<tr>
<td>Backup Data CPU Subsystem</td>
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<td>●</td>
<td>●</td>
<td></td>
<td>●</td>
<td>○</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>Video Signal Processor Subsystem</td>
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<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>○ Test Equipment</td>
</tr>
<tr>
<td>Mission Manager's Workstation</td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>○</td>
</tr>
<tr>
<td>Network Manager &amp; Test Workstation</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>○</td>
</tr>
<tr>
<td>Remote Principal Investigator Workstation</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>○</td>
</tr>
<tr>
<td>Cavity Pre-Cool Subsystem</td>
<td>●</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>○ Coding</td>
</tr>
<tr>
<td>Broadband Local Area Network</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>○</td>
<td></td>
<td></td>
<td>○ Network, Monitors</td>
</tr>
<tr>
<td>Video Distribution Subsystem</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>○</td>
<td></td>
<td></td>
<td>○ Printer, Plotter, WWV Receiver</td>
</tr>
<tr>
<td>Miscellaneous Peripheral Equipment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>○</td>
<td></td>
<td></td>
<td>○ Ground Base System Link</td>
</tr>
<tr>
<td>Ground Base System Link</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>○</td>
<td></td>
<td></td>
<td>○ Ground Base System See separate description</td>
</tr>
</tbody>
</table>

4-207
LOCAL AREA NETWORK

- Plotters
- Printers
- Personal Computers (IBM or Equivalent)
- Simulator
- Operating System Software
- Terminals
- Mass Storage (Hard Disks and Tape Drives)
- Central Computer
- Aircraft System Link

GROUND BASE SYSTEM
FEASIBILITY ASSESSMENT

• FOR THE DMAC SYSTEM, PROVEN TECHNOLOGY AND SYSTEM STANDARDS ARE UTILIZED AS MUCH AS PRACTICABLE

• THE CRITICAL SUBSYSTEMS ARE BASED ON SIMILAR SUBSYSTEMS UTILIZED ON THE KUIPER AIRBORNE OBSERVATORY (KAO). OTHER SUBSYSTEMS HAVE BEEN ADDED TO INCREASE EFFICIENCY AND PERFORMANCE, ALL OF WHICH UTILIZE PROVEN TECHNOLOGY

• THROUGH PROPER SELECTION OF THE LAN, CURRENT AND LONG TERM REAL-TIME CONTROL AND DATA COMMUNICATIONS NEEDS CAN BE MET
SUMMARY

As well as off-line and on-line system monitoring to minimize system downtime, a network manager and test station to provide network management to the data CPU in the event of a failure of the data CPU, backup data CPU is provided for switch over with minimal down time.

Backup data CPU is provided for switch over with minimal down time.

Network manager and test station to provide network management to the data CPU in the event of a failure of the data CPU.

Backup data CPU is provided for switch over with minimal down time.

Modification, protocols, and experimentation interface.

Industry standard network (LAN) to simplify system communication.

To reduce system implementation, maintenance, and cost standardization and use of off-the-shelf hardware and software.

SUMMARY
OPEN ISSUES AND MAJOR CONCERNS

CONCERNS

• RECOMMEND THAT STANDARDIZATION OF HARDWARE AND OPERATING SYSTEM BETWEEN SUBSYSTEMS BE CONSIDERED AS A MEANS TO REDUCE COSTS, REDUCE TIME TO IMPLEMENT, AND SIMPLIFY MAINTAINABILITY
based on reported data on the emissivity of all.

Radiation temperatures for the atmosphere at 40,000 ft. All studies have been estimated to be 272 K. The effective steam air temperature is -70 deg. F.

Altitude of 40,000 ft and phase no. of deg. / the completed recovery temperature is 50 deg. F (free air)

Insulation between the structural beams and / additional insulation between the beams. The walls have 6" of urethane foam

The cavity is assumed to be in the shape of a truncated rectangular pyramid. The top of the cavity is

The cavity expansion, optical deflection due to all deflection and structural deformation due to uneven thermal

Sky was employed to generate the model. These coordinates together with other inputs (conduction, convection, and

A thermal model represents the BOPIA Telescope and cavity has been developed and analyzed using

4-6
are covered with 1/2" thick foam insulation. The cameras and gyroscope system box and located at the bottom of the primary mirror mount. The cameras and gyroscope system are located on the outside of the upper metering tube. The gyroscope system is a 24" x 16" x 10".

Tracker Cameras, Acquisition Camera, and Gyroscope: The cameras are 10" dia. x 36" long and covered with 1" Nansuthy Chamber. The modeled Nansuthy chamber is 72" dia. x 72" long and covered with 1/2" thick Epoxy. The primary mirror is 15". The mirror mount has overall dimensions of 12" dia. x 14" H and is made of ULT material with 3" x 6" struts, 0.6" top plate, and 0.5" bottom plate. The overall thickness of the model used is 0.06" and the primary mirror is made of Corning's glass. The center piece is a rectangular shape on the upper part of the primary mirror and cylindrical shape on the bottom piece. The overall dimensions for the upper piece are 12" dia. x 40" H and for the lower piece are 12" dia. x 42" H.

Dimensions for the upper piece are 12" dia. x 40" H and for the lower piece are 12" dia. x 42" H.

The telescopes and related equipment.
Consider a simplified model of the convection current as sketched below:

\[ n = \text{index of refraction} = 1 + \frac{B}{\rho g} \]

Where

- \( B \) = density of air
- \( \rho \) = density of air
- \( g \) = constant = 0.000293 for air

Refractive index of air is a function of the density as expressed in the Clausius-Dalton Equation:

If the surface temperature of a solid is different from that of the surrounding air, a convection current begins.
MATERIAL PROPERTIES

(a) ALL MIRROR SURFACES HAVE EMISSIVITY OF 0.04. ALL OTHER SURFACES ARE ASSUMED TO BE COATED WITH BLACK PAINT WITH EMISSIVITY OF 0.94. THE SKY IS MODELED AS A BLACK BODY AT -221°F.

(b) CONDUCTIVITIES (UNITS IN BTU/HR°F/FT):

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALUMINUM</td>
<td>73 AT -148°F, 92 AT 32°F</td>
</tr>
<tr>
<td>INVAR</td>
<td>6.2</td>
</tr>
<tr>
<td>GRAPHITE EPOXY</td>
<td>17 (ISOTROPIC)</td>
</tr>
<tr>
<td>CORNING'S ULE MATERIAL</td>
<td>0.75</td>
</tr>
<tr>
<td>URETHANE FOAM INSULATION</td>
<td>0.023</td>
</tr>
<tr>
<td>STAINLESS STEEL (BOLTS)</td>
<td>8.1</td>
</tr>
<tr>
<td>FIBERGLASS (THERMAL ISOLATOR)</td>
<td>0.09</td>
</tr>
</tbody>
</table>

(c) SPECIFIC HEAT (UNITS IN BTU/ LB/°F):

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALUMINUM</td>
<td>0.15 AT -200°F, 0.2 AT 0°F</td>
</tr>
<tr>
<td>INVAR</td>
<td>0.11</td>
</tr>
<tr>
<td>GRAPHITE EPOXY</td>
<td>0.25</td>
</tr>
<tr>
<td>CORNING'S ULE MATERIAL</td>
<td>0.183</td>
</tr>
</tbody>
</table>

HEAT SOURCES

<table>
<thead>
<tr>
<th>Heat Source</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRACKER CAMERA</td>
<td>105 W (KAO DATA)</td>
</tr>
<tr>
<td>ACQUISITION CAMERA</td>
<td>105 W (KAO DATA)</td>
</tr>
<tr>
<td>GYROSCOPE</td>
<td>150 W (KAO DATA)</td>
</tr>
<tr>
<td>SECOND MIRROR CHOPPER</td>
<td>50 W (ESTIMATE)</td>
</tr>
<tr>
<td>AIR BEARING SUPPLY AIR</td>
<td>15 SCFM (KAO NO. X 3)</td>
</tr>
<tr>
<td>AIR LEAKAGE FROM CABIN</td>
<td>150 LB/HR (ESTIMATE)</td>
</tr>
</tbody>
</table>

THE CAMERAS AND GYROSCOPE SYSTEM ARE MOUNTED ON THE TELESCOPE. IT IS ASSUMED THAT EACH INSTRUMENT IS FASTENED TO THE TELESCOPE WITH EIGHT STAINLESS STEEL BOLTS (1/4" DIA.). TO REDUCE HEAT TRANSFER, FIBERGLASS SPACERS (1" O.D, 0.3" I.D, 1" LONG) ARE PROVIDED AT EACH BOLTED JOINT.
In the area between the primary mirror and its support, natural convection is assumed, and the flow is more likely to be turbulent.

Usually when Reynolds no. is less than 30000, the flow is considered to be laminar. In the vicinity when Reynolds no. is at least 40000, the flow type is estimated to be 0.169.

### Flow Type

<table>
<thead>
<tr>
<th>Re</th>
<th>Flow Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>Turbulent</td>
</tr>
<tr>
<td>0.95</td>
<td>Turbulent</td>
</tr>
<tr>
<td>1.51</td>
<td>Turbulent</td>
</tr>
<tr>
<td>2.00</td>
<td>Laminate</td>
</tr>
</tbody>
</table>

### Location

\[ H = 0.037 \times \text{Re}^{0.8} \times \frac{p}{\mu} \times \frac{L}{h} \]

### Table

<table>
<thead>
<tr>
<th>Location</th>
<th>Re</th>
<th>Dc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Close to</td>
<td>15</td>
<td>a</td>
</tr>
<tr>
<td>Primary</td>
<td>10</td>
<td>b</td>
</tr>
<tr>
<td>Secondary</td>
<td>5</td>
<td>c</td>
</tr>
<tr>
<td>Mirror</td>
<td>1</td>
<td>d</td>
</tr>
</tbody>
</table>

### Flow for Turbulent Flow

\[ H = 0.964 \times \text{Re}^{0.8} \times \frac{p^{1/3}}{\mu} \times \frac{L}{h} \]

### Convective Heat Transfer Coefficients

- Close to the cavity
- Middle of the cavity
- Upper 1/3 of the cavity
- Secondary mirror and supporting structures
- Bottom 1/3 of the cavity
- Middle 1/3 of the cavity
- Upper 1/3 of the cavity

### Convective Heat Transfer Coefficients

The cavity has been estimated as follows:

Utilizing Boundary Preliminary Computational Fluid Dynamics (CFD) results, the flow velocities within

\[ \text{Velocity} \times \text{Re} \times \text{Pr} \times \text{Fo} \times \text{Gr} \]
CAVITY AIR TEMPERATURE

IF THERE IS NO HEAT GAIN OR LOSS IN THE CAVITY, THE AIR TEMPERATURE IN THE CAVITY EQUALS THE RECOVERY TEMPERATURE (-25°F FOR 40,000 FT. AND MACH NO. 0.8). IN THE SOFIA CASE, THE AIR TEMPERATURE CAN BE ESTIMATED BY CONSIDERING AN ENERGY BALANCE FOR THE CAVITY.

HEAT FLOWS INTO THE CAVITY (BTU/HR):

<table>
<thead>
<tr>
<th>Description</th>
<th>BTU/HR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Through the walls</td>
<td>4623</td>
</tr>
<tr>
<td>Through air bearing</td>
<td>324</td>
</tr>
<tr>
<td>Air supply to air bearing</td>
<td>770</td>
</tr>
<tr>
<td>Power to chopper</td>
<td>171</td>
</tr>
<tr>
<td>Power to cameras</td>
<td>716</td>
</tr>
<tr>
<td>Powder to gyroscope</td>
<td>512</td>
</tr>
<tr>
<td>Air leakage through walls</td>
<td>3420</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>10536</strong></td>
</tr>
</tbody>
</table>

HEAT FLOW FROM CAVITY TO OUTSIDE ATMOSPHERE BY RADIATION = 9280 BTU/HR

NET HEAT FLOW INTO CAVITY AND ABSORBED BY CAVITY AIR = 1256 BTU/HR

MASS FLOW INTO CAVITY FROM THE SHEAR LAYER = 14 LB/SEC

TEMPERATURE RISE OF CAVITY AIR = 1256/(14 x 3600 x 0.24) = 0.1°F

AS SHOWN, THE CAVITY AIR TEMPERATURE RISE IS VERY SMALL AND CAN BE NEGLECTED. THUS, IN ALL THE ANALYSES, THE CAVITY AIR TEMPERATURE IS ASSUMED TO EQUAL THE RECOVERY TEMPERATURE.
The chart shows steady state temperatures for all the nodes.

<table>
<thead>
<tr>
<th>Node</th>
<th>Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-9</td>
<td>31.5</td>
</tr>
<tr>
<td>77.9</td>
<td></td>
</tr>
<tr>
<td>27.4</td>
<td></td>
</tr>
<tr>
<td>27.4</td>
<td></td>
</tr>
<tr>
<td>27.4</td>
<td></td>
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<tr>
<td>27.4</td>
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<td>27.4</td>
<td></td>
</tr>
<tr>
<td>27.4</td>
<td></td>
</tr>
<tr>
<td>27.4</td>
<td></td>
</tr>
</tbody>
</table>

The calculated steady state temperatures are as follows (in deg. F):

- Recovery temperature (in the cavity) = -2.9°F
- Free stream air static temperature = -9.0°F
- Mach NO = 0.5
- Altitude = 4000 ft

For a period of 2-5 hours, the assumed ambient conditions are:

- Ambient temperature and the ambient air temperature at the operating altitude with constant ambient conditions.

The steady state solution applies to the case when the telescope and cavity are pre-cooled to near the
Telescope. The time constants have been estimated from the case I results as follows:

The figures on the next two pages show temperature response for the major components of the telescope. The majority, drops to -25°F in 20 minutes, then stays constant at -25°F for the remainder of the flight. Cavity air temperature increases from -5°F to +5°F in 20 minutes, holds slowly at +5°F for 20 minutes, and then stays at +5°F for the remaining time of the flight. In the second case, the cavity air temperature increases from -25°F to +10°F for two cases. In the first case, it is assumed that the cavity air temperature increases from -25°F to +10°F.

Transient Analysis
Conclusions for Telescope and Cavity Thermal Analysis

A. Steady state analysis

1. Radiation is a significant mode of heat transfer and it causes temperature variation of approximately 6°F between the top and the bottom of the telescope.

2. Top surface of the primary mirror has a uniform temperature of -25.6°F. Since this is very close to the recovery temperature (-25°F), little optical "seeing" is expected.

3. Secondary mirror assembly is 2.1 to 6.9 degrees above the recovery temperature and this can cause a seeing effect of 0.4 arcsec. The present analysis assumes a 50 W heat dissipation for the chopper. If the true power input is higher, special heat rejection design will be required.

4. Air bearing operates at +28.7°F, but it is not likely to cause optical seeing since the light path (to Nasmyth instruments) is parallel to the direction of the density gradient. Air bearing does not cause excessive heating of the telescope since the connecting tube is made of Invar which has a low thermal conductivity.

5. Heat sources (tracker camera, acquisition camera, gyroscope) cause temperature variations up to 15.6°F in the telescope structure. If desired, these gradients can be reduced with better thermal isolators.

B. Transient analysis

1. The transient results show that if the cavity temperature experiences a 20°F temperature change, the top surface of the primary mirror will reach a 10°F approach to the cavity temperature (with an optical seeing effect of 0.6 arcsec) in about 1.2 hour.

2. For a "ramp" input with temperature change of 20°F and duration of 20 minutes, maximum temperature change for the primary mirror is 5.5°F with a seeing effect of 0.3 arcsec.
TEMPERATURE RESPONSE IN FLIGHT RAMP INPUT

TIME (HOURS)
4-225
The following methods of cooldown have been studied:

- SINDA (Simplified Integral, Numerical, Difference, Analytical).
- SPTA (Simplified Ptential, Thermal, Analytical).

The models of the cell are calculated by the program present: Reduction of temperature of bottom edge. R. Conduction, convection, and radiation models of heat transfer are all temperatures of -70 deg. The mirror is initially at 70 deg. and after time, it is exposed to a constant airflow at a chart. The mirror is initialized at 70 deg. and after time, it is exposed to a constant airflow at a chart. The mirror is initialized at 70 deg. and after time, it is exposed to a constant airflow at a chart.

For the present analysis, it is assumed that there are no temperature gradients in the radial and circumferential directions and as a result, a simple model consisting of only one cell was employed (see afterwards). For the present analysis, it is assumed that there are no temperature gradients in the radial and circumferential directions and as a result, a simple model consisting of only one cell was employed (see afterwards).

<table>
<thead>
<tr>
<th>Property</th>
<th>Specific Heat</th>
<th>Conductivity</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.133 Btu/ft²°F</td>
<td>0.75 Btu/hr/ft²°F⁻¹</td>
<td>1.79 lb/cu ft</td>
</tr>
</tbody>
</table>

Follows: Between 8" at the center and 12" at the outer edge. Thermal properties for the ULT material are as above 8" at the center and 12" at the outer edge. Thermal properties for the ULT material are as above 8" at the center and 12" at the outer edge. Thermal properties for the ULT material are as above 8" at the center and 12" at the outer edge. Thermal properties for the ULT material are as above 8" at the center and 12" at the outer edge. Thermal properties for the ULT material are as above.
The above quantities and equations are programmed into SINDA's input and the heat transfer coefficients are evaluated before each iteration.

1. If \( GP \times Pr < 1068 \),
   \[ C = 0.12', \ W = 1/3 \]

2. If \( GP \times Pr > 1068 \),
   \[ C = 0.50', \ W = 1/4 \]

For the struts, use average values for vertical and horizontal plates:

1. If \( GP \times Pr < 1068 \),
   \[ C = 0.13', \ W = 1/3 \]

2. If \( GP \times Pr > 1068 \),
   \[ C = 0.59', \ W = 1/4 \]

The end plates of the mirror are considered as vertical plates:

The values of \( \rho, \mu, \) and \( K \) are properties of the fluid film and are evaluated at the average temperature \( T_m \). The values of \( \rho_0, \mu_0, \) and \( K_0 \) depend on the magnitude of \( GP \times Pr \) as well as the inclination of the plate.

\[
\begin{align*}
K & = \text{Thermal Conductivity, psi/hr-ft-\degree F} \\
\rho & = \text{Density, lb/ft}^3 \\
C_p & = \text{Specific Heat, Btu/lb-\degree F} \\
\mu & = \text{Viscosity, lb/hr-ft} \\
\rho_0 & = \text{Density, lb/ft}^3 \\
C_{p0} & = \text{Specific Heat, Btu/lb-\degree F} \\
\mu_0 & = \text{Viscosity, lb/hr-ft} \\
\rho_0 & = \text{Density, lb/ft}^3 \\
T & = \text{Fluid Temperature, \degree F} \\
T_{\infty} & = \text{Wall Temperature, \degree F} \\
T_m & = \text{Average Temperature, \degree F} \\
\rho & = \text{Density, lb/ft}^3 \\
L & = \text{Length of the plate, ft} \\
G & = \text{Acceleration of Gravity, 4,178 \text{ ft/sec}^2} \\
\mu(N) & = \text{Reynolds Number, \text{ Re } = \frac{L \times \rho \times C_{p0} \times (T_m - T_0)}{\mu_0 \times N^2}} \\
H & = \text{Heat Transfer Coefficient, Btu/hr-ft-\degree F} \\
H = \frac{C \times (Pr \times GP)}{W} \times K/L
\end{align*}
\]

Where:

\[ H = \frac{C \times (Pr \times GP)}{W} \times K/L \]
PRIMARY MIRROR
NATURAL CONVECTION ONLY

Temperature (deg. F)

Time (hours)

4-229
of other flow conditions. Time constants have been calculated and tabulated for the above cases and a number of different flow rates. The results of computation are presented as graphs of temperature versus time and time constants.

The results of computation are presented as graphs of temperature versus time and time constants.

**Heat Transfer Coefficients.**

Natural convection cannot be ignored. Total heat transfer coefficient is the sum of the coefficient of the tube entrance has been neglected.

It is noted that the H value due to forced convection is rather small (0.2) and therefore the following formula is applicable (effect of the tube entrance has been neglected):

For all flow rates considered, the flow in the cell is laminar (Re < 2000), and the following formula applies:

\[ H = \frac{0.66 \times K/L}{Re} \]

\[ H = \frac{0.025 \times Re^{0.8} \times Pr^{0.6} \times K/L}{Re} \]

Where

\[ Re = \frac{Reynolds \, no. \times \rho x A \times \bar{V}}{\mu} \]

\[ Pr = \frac{C_p \times \mu}{\lambda} \]

\[ A = \text{Surface Area} \]

B. **Blowing in the Cell**

- H, \(\mu\), \(\rho\), \(\nu\), and \(\lambda\) are as defined in the natural convection section.

A. **Surface Blowing**

- Heat Transfer Coefficients for Forced Convection
due to the complexity of mechanical design and fabrization (over 1000 tubes are required).

4.2 When blowing provides faster cooldown with lower flow rates, however, it is not recommended.

As a result, total flow rate requirement for the case has been estimated to be 4000 cfm/mn.

Surface blowing at 20 ft/sec reduces the time constant to 1 hour and represents an optimum
considered inadequate.

The "no blowing" case resulted in fairly high time constant (2.5 hours) and is therefore
thermal mass and coefficient of expansion.

Combining "Nile" appears to be a desirable material for the primary mirror due to its low
Conclusion: For Primary Mirror Cool-down Analys
# PRIMARY MIRROR TIME CONSTANT (RESULTS)

## TIME CONSTANTS (HOURS)

<table>
<thead>
<tr>
<th>CASES</th>
<th>MIRROR SURFACE</th>
<th>STRUT (MIDDLE)</th>
<th>BOTTOM SURFACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO BLOWING</td>
<td>1.7</td>
<td>2.3</td>
<td>1.7</td>
</tr>
<tr>
<td>BLOWING OVER TOP &amp; BOTTOM SURFACES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$V = 10 \text{ FT/S}$</td>
<td>0.75</td>
<td>1.5</td>
<td>0.78</td>
</tr>
<tr>
<td>$V = 20 \text{ FT/S}$</td>
<td>0.40</td>
<td>1.1</td>
<td>0.45</td>
</tr>
<tr>
<td>$V = 30 \text{ FT/S}$</td>
<td>0.25</td>
<td>0.95</td>
<td>0.28</td>
</tr>
<tr>
<td>$V = 40 \text{ FT/S}$</td>
<td>0.18</td>
<td>0.85</td>
<td>0.18</td>
</tr>
<tr>
<td>$\text{N}_2$ BLOWING IN CELL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 MIRROR MASS/HR</td>
<td>0.35</td>
<td>0.45</td>
<td>0.80</td>
</tr>
<tr>
<td>$V = 3.7 \text{ FT/MIN}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 MIRROR MASS/HR</td>
<td>0.35</td>
<td>0.25</td>
<td>0.60</td>
</tr>
<tr>
<td>3 MIRROR MASS/HR</td>
<td>0.30</td>
<td>0.20</td>
<td>0.50</td>
</tr>
<tr>
<td>4 MIRROR MASS/HR</td>
<td>0.30</td>
<td>0.17</td>
<td>0.50</td>
</tr>
<tr>
<td>5 MIRROR MASS/HR</td>
<td>0.30</td>
<td>0.17</td>
<td>0.50</td>
</tr>
</tbody>
</table>

4-233
control over the telescope.

 requirement incorporated within the SOPIA control and data system.

 Observing time is maximized by incorporating a computer aided telescopic recognition. This is a

 SOPIA system emulation is supported by a series of programs written in C, that allow the

 transferred, a continuous type interface (8 data parallel plus strobe) is a leading candidate.

 Complementarity of the experimenters system with SOPIA is achieved by using standard serial

 that it may function independently and as a stand-alone facility.

 Archiving of the experimenters data is provided by a system which keeps a log of all selected data.

 Data collection by the experimenters is paramount, requiring only target acquisition and a

 Instrument Accommodations
EXPERIMENTER INTERFACE REQUIREMENTS

- DATA COLLECTION IS PARAMOUNT
- DATA ARCHIVING FOR LATER ANALYSIS
- COMPATIBILITY TO MINIMIZE SYSTEM INTEGRATION TIME
- SOFIA SYSTEM EMULATION FOR EARLY VERIFICATION
- MAXIMUM OBSERVING TIME
- EASE OF USE
The observer also has the option of making observations without the use of the experimental computer. In addition to the experimental computer, a data archiving facility capable of accepting raw data directly sends the experimentalist with a record of all data taken during the flight.

The experimental system with selected telescope system parameters is environmental. This archiving facility will provide the experimentalist with a record of all data taken during the flight.

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Object oriented programming is a departure from past practices but has the advantage of being easy to understand and lends itself to low cost modification of the information presented or the operational environment. Compatibility possible between ground based observatories and SOPFIA.

Heavily emphasis on graphical displays and object oriented programming will insure the greatest efficiency.“
EXPERIMENTER INTERFACE
DISPLAY TECHNIQUES

PREACQUISITION MODE

TELESCOPE POINTING MODE

TELESCOPE TRACKING

EXPERIMENTER CONTROL
SECTION 5
AIRCRAFT SYSTEM DESCRIPTION

5.1 Introduction
5.2 Aircraft System Requirements Summary
5.3 Aircraft and Cavity Modification Concept
5.4 Cavity Environmental Control
5.5 Aircraft Interfaces
5.6 Conclusions and Major Issues
Introduction
AIRCRAFT MODIFICATION STUDIES BACKGROUND

- NASA/ARC INITIATED TELESCOPE SYSTEM AND AIRCRAFT MODIFICATION STUDIES FOR SOFIA, 1986

- BOEING 747 ESTABLISHED AS ONLY AIRCRAFT TYPE CAPABLE OF MEETING ALL REQUIREMENTS

- BOEING MILITARY AIRPLANE COMPANY AWARDED 2-PHASE CONTRACT TO STUDY AIRCRAFT MODIFICATION, PERFORMANCE, AND COST

- PHASE I STUDY ESTABLISHED UPPER LIMIT TO TELESCOPE SIZE FOR A PROGRAM OF REASONABLE COST

- PHASE II STUDY (COMPLETED AUGUST 1987) REFINED CONCEPT, PERFORMANCE, AND COSTS ASSOCIATED WITH A 3-METER F/1 TELESCOPE IN A BOEING 747SP
Study Objectives:

The primary goal of the contracted Phase A aircraft modification system level studies was to establish equipment, mission equipment installation and integration, and identification of issue and technical problems of a conceptual configuration that is not cost prohibitive, yet satisfies system level requirements and provides an end state platform for increased autonomy. The Phase I study objectives were developed.
PHASE II STUDY OBJECTIVES

- ESTABLISH AND DOCUMENT PRIMARY AIRCRAFT/SUBSYSTEM REQUIREMENTS (WITH ARC)
- DETERMINE DRAG/PERFORMANCE PENALTY OF CAVITY AND BLC CONCEPTS
- DEVELOP STRESS DATA AND ANALYSES TO VALIDATE STRUCTURAL MODIFICATION CONCEPT
- REFINE MODIFICATION CONFIGURATION CONCEPT
  - 3.0 METER TELESCOPE (PRIMARY DIAMETER)
  - 20°-60° ELEVATION FIELD OF VIEW - UNVIGNETTED
  - POROUS FENCE AND AFT RAMP FOR BLC
  - AFT BULKHEAD/RAMP/DOOR CONFIGURATION DETAILS
  - DOORS AND FENCE THAT TRACK TELESCOPE MOTION
  - THERMAL AND ACOUSTIC ISOLATION CONCEPTS
  - UPDATE "LOPA" AND WEIGHT AND BALANCE
  - IDENTIFY SPECIALIZED GROUND SUPPORT EQUIPMENT
  - IDENTIFY INTERFACES/ACCOMMODATIONS
- ESTABLISH REQUIREMENTS SENSITIVITY
- DEVELOP COST/SCHEDULE FOR REFINED CONCEPT
in the Statement of Work specifications for the BMD aircraft modification study contract.

A communication interface exists between the mission computer (CPU) and the aircraft's Automatic Flight Control System. The interface transmits data from the aircraft's avionics to the CPU, allowing for the integration of mission-critical information into the aircraft's flight control system. The interface supports the transmission of data related to flight parameters, mission objectives, and other critical information necessary for the safe and efficient operation of the aircraft.

The SOFIA aircraft's mission requirements fall into three basic categories: short-term, medium-term, and long-term. The short-term requirements are focused on the immediate mission objectives, such as data collection, equipment maintenance, and crew support. The medium-term requirements address the long-range mission objectives, such as data analysis, mission planning, and equipment modification. The long-term requirements support the overall mission objectives, such as equipment upgrades, crew training, and mission planning.

The aircraft's mission is designed to support scientific research and data collection. The aircraft's mission parameters include the mission duration, altitude, and speed, as well as the mission objectives, such as data collection, equipment maintenance, and crew support. The aircraft's mission is designed to support the scientific research and data collection needs of the research community.
SUMMARY OF AIRCRAFT SYSTEM REQUIREMENTS

• AIRCRAFT PERFORMANCE
  - CLIMB TO FL410, EST. CRUISE CONDITIONS, AND OPEN DOOR WITHIN 30 MINUTES
  - MAINTAIN ALTITUDE ≥ FL410 FOR AT LEAST 6.5 HOURS WITH DOOR AND BLC FENCE OPEN
  - DEPLOYMENT MISSION: ≥ 6000 N.M. RANGE WITH IFR RESERVES (DOOR CLOSED)
  - ATTITUDE ACCURACY/STABILITY: ≤ ±0.5° RMS AZIMUTH, ROLL AND PITCH AXIS

• MISSION EQUIPMENT/CREW ACCOMMODATIONS
  - EQUIPMENT MOUNTING PROVISIONS (CONSOLES, RACKS, ETC.), TO WITHSTAND EMERGENCY/CRASH LOADS
  - CABIN TEMPERATURE, PRESSURE, HUMIDITY, AND SOUND LEVEL LIMITS
  - PROVISIONS FOR SAFETY EQUIPMENT AND ANNUNCIATORS, GALLEY, AND LAVATORIES
  - PROVISIONS FOR COMMUNICATIONS (INTERPHONE) AND ELECTRICAL POWER INTERFACES
  - INSTALLATION ACCOMMODATIONS FOR POWER AND COMMUNICATIONS CABLES
  - PROVISION OF ADDITIONAL SEATING FOR FERRY PASSENGERS
  - PROVISION OF PORT(S) FOR WATER VAPOR MONITOR(S)
  - ACCOMMODATE AIR COMPRESSORS, VACUUM PUMPS, AND NITROGEN TANKS WITH LINE ROUTING
  - PROVIDE SIGNAL INTERFACE BETWEEN AUTOPILOT/AIR DATA COMPUTER AND MISSION CPU
Several additional cavity requirements relate to accommodation equipment routing and access. These requirements are depicted in several of the figures which follow. The chart summarizes the requirements levied on the aircraft cavity accommodation system. (Cont.)
SUMMARY OF AIRCRAFT SYSTEM REQUIREMENTS (CONT'D)

• AIRCRAFT CAVITY SUBSYSTEM
  - VOLUME: ACCOMMODATE 156" DIA. x 151" L. TELESCOPE WITH +20-60° UNVIGNETTED ELEVATION RANGE AND ± 2° (TBD) LOS/AZIMUTH RANGE, WITHOUT INTERFERENCE
  - MASS: CAVITY MOD. WEIGHT ≤ 16,000 LBS (ABOVE STANDARD CONFIGURATION)
  - THERMAL ISOLATION: CABIN/CAVITY THERMAL TRANSFER ≤ 2000 W (GOAL, AT ALTITUDE)
  - CAVITY OPENING: 146" x 210" (FULLY OPEN; CONSISTENT WITH MOTION REQUIREMENTS)
  - CAVITY DOOR: DEPLOYABLE/RETRACTABLE IN-FLIGHT AND ON GROUND OPENING TIME ≤ 3 MINUTES DOOR OPENING TO TRACK TELESCOPE ELEVATION (I.E., 2-PIECE DOOR)
  - SHEAR LAYER CONTROL: BLC FENCE AND AFT RAMP; FENCE TO TRACK TELESCOPE ELEVATION
  - FEEDTHROUGHS: AFT BULKHEAD PROVISIONS FOR CABLE/PNEUMATIC LINE FEEDTHROUGHS
  - ENVIRONMENTAL: ACCOMMODATE GROUND AND AIRBORNE CAVITY COOLING/DEHUMIDIFICATION/HEATING INTERFACES
  - BULKHEADS: ACCOMMODATE VIBRATION ISOLATION SYSTEM MOUNT, AIR BEARING "HOLE" AND WINDOWS ON AFT BULKHEAD; PROVIDE ACCESS DOOR AND TELESCOPE LOCKING DEVICE ON FORWARD BULKHEAD

5-9
I

Fuel tank, hole for installation of a water vapor monitor.

Power distribution panel is located forward of the cabin partition, near a 4-inch diameter upper access hole through the standard external cargo door and a bulk floor mounted hatch and ladder. A crewman "wading" for从容 in the aft section and one forward of the cavity. The cargo compartment is crewmen and passengers' rear. Passengers located in the underfloorized tail area, five passenger doors. Crewmen enter/maintaining/communication/cooling are located in the aft compartment, and the L2 blankets for their protection. Intercommunication is shown in the aft cargo compartment, and the L2 blankets for their protection. Rigid blankets, waterproof and ventilated (inflation system) are located in the aft compartment and the L2 blankets for their protection.

With a console seat and equipment rack, access to the Navigational Instrument. One of the equipment positions is located beside the counterweight. An equipment hole is provided above the instrument mounting. An equipment slot is provided in both cabin floors for access to the under-floor tunnel exits.

The following chart details the SOFIA platform for the Boeing 747-SP.
LAYOUT FOR PERSONNEL ACCOMMODATIONS (LOPA) (CONT'D)
Cavity Floor: Enables transfer of cold air from the ground cooling system through a fuselage port to a port in the main deck floor. In the cavity to minimize modification cost and complexity, the "hidden" ground cooling duct location is effective. As discussed in Section 3, the cavity weight would be more weight-efficient if it were longer and narrower. The concept keeps the main deck floor in its standard location on the airplane weight. Although the chart shows the upper deck floor beams are to be deleted in the area of the cavity, the actual need for this will depend on the final remaining fuselage structure around the cavity. The envelope surrounding the cavity. Although the chart shows that the upper deck floor beams are to be deleted in the area of the cavity, the actual need for this will depend on the final remaining fuselage structure around the cavity. The envelope surrounding the cavity.
constant (as close as possible) deflection under presstilation at points of contact with the apr bearing.

is 10 inches, with 0.03 Ege 2024 skins. The chord members of the inner circle are sized to maintain a
certain perimeter with internal ribs every 15 degrees from the inner circle radius. The large box depth
material and chords in compression are 7075 material. Loads from the bulkhead are transmitted to the
consists of a closed torque box attaching to the telescopes of the inner circle and to the bulkhead at the
side of the body skin with intercostals located between existing struts. The telescopes support
bonded steps at beam locations to prevent tearing at fasteners. Beam chords in tension are 2024
widths. If regarded, the bulkhead web is 0.06-inch 2024-T3 aluminum for pressure, with 0.06-inch
center of the bulkhead is provided by adding ribs at extensions that can be tailored for loads to save
are made failpaque by using dual chord caps and web. Additional beam strength at the
The main beams (2 vertical and 2 horizontal) surrounding the apr bearing culvert as well as other highly
vertical struts are located every 10 inches.

limits of 1/2 degree or not exceed the bulkhead at the telescopes rotation at 9.4 psi. 20 inch long
beams are 20 inches deep and are "hard" designated. This design maintains maximum deflection
of the inner rings from 600 to 1500 in. (real moment) depending on beam length and location. The
pressure of 9.4 psi. The construction of the intersecting beams at 20 inch spacing with a moment
bearing load based on 7 factors of the maximum yield pressure of 9.4 psi. For normal operation
The apr bulkhead of the cavity housing the telescopes is designed for 18.8 psi pressure (the ultimate

AT Cavity Bulkhead Structure

Cavity Modification Concept (Contd)
Recessions will require further analysis to verify design adequacy.

Inches (frame bays) in length, others will be 20 inches long. The "kick" loads on radial frame located between existing body stringers. The higher-loaded intersections will spread the load over 40 bulkheads. The bulkhead to skin intersections are basically back-to-back angles for failure design. The bulkhead is skin thickness. From pressure loading variation, the bulkhead is strength designed with at least moments of 600 to 1000 in. depending on beam location and length. The loads from the bulkhead are transmitted to the skin of the shoulder between the stringers, extending forward of the transom to the skin or body stringers by the transom to the skin or bulkhead, extending forward of the transom to the skin.

The P.S. 530 (Forward) pressure bulkhead is also designed for 18 psi (2 factors on sheet metal). The...
studied in an earlier concept for a 4.5 meter telescope. The issue was
notifying of the need. To allow the floor of the lower floor to be quite cost prohibitive. This issue was
necessitated by a reduction in telescope size or motion ranges. It has already been established that
locating and control was to the telescope as possible. Of course, the ultimate resolution if it becomes
possible to improve clearances in these areas by modifying the geometry of possible, for a large
both the telescope and cavity. The location of a stress point having been established, it is incumbent
on both sides to improve clearances with all the clearances in mind. So little can be gained by
(degree point) has been established with all the clearances in mind. So little can be gained by
(stress point) adds directly to the telescope and cavity. The location of the center of rotation
in limiting conditions or the addition of the telescope and cavity, which may be up to 1
science considerations. In addition, the apparent isolation system trapped, which may be up to 1
becomes almost nonexistent. Indeed, there may be a need to increase the cross-elevation range due to
the current 9 x 2 cross-elevation angular range in factored into the "closed-elevation" clearance.
issue is the proximity of the rotation center to the loop itself. As can be seen, clearances are not generous.
and 60 degree above horizontal. As can be seen, clearances are not generous.
The 2-meter telescope concept detail provided by MWJ to ARCS is shown in its two extreme
the diagram depicts the cavity volume available at the telescope centerline, located at F's. 601.6.

Cavity Geometry (cont)
The door extends from R.G. 52 to R.G. 62. Its depth is 4 inches with an 40 outer skin and 40 inner skin with access holes for pressure relief and resistant installation access. The door provides an external fire barrier with fire-resistant joints, including 4 inches with an 40 outer skin and 40 inner skin with access holes for pressure relief and resistant installation access. The door extends from R.G. 52 to R.G. 62. Its depth is 4 inches with an 40 outer skin and 40 inner skin. With the configuration, the forward and all door tracks can be located in the cavity. The cavity modification concept (cont'd).
CAVITY DOOR INSTALLATION

- Upper Door Closed Position
- Outer Contour STA 520
- Viewing Area Upper Elevation
- Line of Sight Upper Limit
- Upper Door Full Open Position
- Rack for Rack & Pinion Door Actuation
- Outer Contour STA 700
- Viewing Area Lower Elevation
- Lower Door Closed Position
- Flex Seal
- Line of Sight Lower Limit
- Lower Door Full Open Position
- Rack for Rack & Pinion Door Actuation
- Track Support Structure
installed on the aft bulkheaded with a flexible seal cutoff for the door penetration.

conclusion

The figure shows a rear view of the deployed segmented fence, which is mounted on the fuselage.

There are many options for controlling the shear layer over the cavity open port, a well-behaved, continuous shear layer is important for minimizing the effects of "sealing" on telescope optical performance. Main options include a passive air ram, above, an artificial ram, with or without the performance. The latter option has been chosen for a conservative approach with minimum complexity for this study. Physical future tunnel testing will be needed to determine the optimum computational model and wind tunnel testing will be needed to determine the optimum.
AERODYNAMIC FENCE CONCEPT

REAR VIEW - FENCE DEPLOYED
Some weight penalty.

The forward pressure buckhead has the same general arrangement except for the access door framing.

The BMC aircraft system concept study included performance of stress analyses in various areas.
STRESS ANALYSES

- FUSELAGE REINFORCEMENT
  - CUTOUT AND MONOCOQUE SIZING
  - RAMP AND FENCE
  - MONOCOQUE REINFORCEMENT
  - CAVITY DOOR
- AFT BULKHEAD
  - CUTOUT FOR TELESCOPE AIR BEARING
  - PRESSURE LOADS
- FORWARD BULKHEAD
  - ACCESS DOOR
  - PRESSURE LOADS
- CAVITY FLOOR
  - BULKHEAD CONNECTION
  - AIRCRAFT TORSION AND BENDING
  - PERSONNEL AND "ABUSE" LOADS
  - ALTERNATE PRESSURIZED CONCEPT
The other drag increments was assigned for this parameter in each mode.

By flow changes on or around adjacent surfaces and the wind root/body intersection a nominal 10% of

tracking (T), including reference position (R) and reference effect corrections, such as drag-generated

removed skin in the open port area (this is subtracted); reference effects for the

grooves/edges between the door segments and circumferential gaps (g) contribute correction for the

door surface (closed, open, or tracking) with corrections for the upper/lower door surfaces (closed;

edge of the door and the contribution of the gap covers over the door hanger/track follower (a) the

edge of the door and the contribution of the gap at the art ramp with corrections for the gaps at the art

forward intersection skin to the door contours (b) the surface step-down from the

mode. The elements area; forward lip and aft-landing step, which is the surface step-down from the

shown as a "flat-plate equivalent" in square feet, and summing the increments for total drag in each

showing the drag analysis was conducted by estimating the effects of each of the drag-producing elements.

Modelled Aircraft Drag Analysis

Still operating worst-case drag and probable strong buffetline.

with door fully open and reference deployed representing a back-up or emergency mode of operation,

Mode I with door and reference deployed the reference (current baseline) and (g) Observation (Mode III,

Mode II with door and reference tracking the reference (current baseline) and (g) Observation (Mode III,

partially open and reference tracking the reference (current baseline) and (g) Observation (Mode III,

with door closed and landing and Reference (2) Observation (Mode III, with door closed and landing

were studied. They were: (i) flight mode, where the door is closed and reference deployed for takeoff,

at forward ramp and a KAO, like reference forward of the open port. Four basic modes and reference positions

are included, in which the open port 180° x 210° in size. An


### SOFIA INCREMENTAL DRAG SUMMARY

<table>
<thead>
<tr>
<th>Flight Mode:</th>
<th>Forward Lip</th>
<th>Alt Ramp</th>
<th>Door Closed (C)</th>
<th>Less Removed Skin</th>
<th>Fence Down (D)</th>
<th>Interference 10%</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Least Drag, for Climb &amp; Ferry)</td>
<td>3.72 sq ft</td>
<td>.40 sq ft</td>
<td>2.46 sq ft</td>
<td>.92 sq ft</td>
<td>1.65 sq ft</td>
<td>.73 sq ft</td>
<td>8.0 sq ft</td>
</tr>
<tr>
<td>Observation Mode I:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fence Retracted, Door Tracking</td>
<td>5.90 sq ft</td>
<td>.55 sq ft</td>
<td>1.12 sq ft</td>
<td>.92 sq ft</td>
<td>1.65 sq ft</td>
<td>.84 sq ft</td>
<td>9.1 sq ft</td>
</tr>
<tr>
<td>Observation Mode II:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Door &amp; Fence Tracking</td>
<td>5.90 sq ft</td>
<td>.55 sq ft</td>
<td>1.12 sq ft</td>
<td>.92 sq ft</td>
<td>12.30 sq ft</td>
<td>1.90 sq ft</td>
<td>20.9 sq ft</td>
</tr>
<tr>
<td>Observation Mode III:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Door Full Open Fence Full Deployed</td>
<td>8.9 sq ft</td>
<td>.64 sq ft</td>
<td>.06 sq ft</td>
<td>.92 sq ft</td>
<td>18.09 sq ft</td>
<td>2.68 sq ft</td>
<td>29.4 sq ft</td>
</tr>
</tbody>
</table>
Airframe endurance is shown on the next chart.

Fuel load is about 14,000 lbs. Aircraft endurance at operating altitude is shown on the next chart.

Maximum ramp of taxi gross weight envelope is - 460,000 lbs, to allow direct ascent to 41,000 ft.

Projected SOFIA zero-Fuel Weight of about 338,000 lbs. The fuel load shown is for a 304,000 lbs of standard airliner provisions deleted, the main deleted items include galleys, structure, and doors and windows, etc. Addition of the baseline payload and ballast (see breakdown in Section 2) would be 98,000 lbs.

The chart shows a breakdown of the SOFIA aircraft mission weight and center of gravity? The letter is...
## SOFIA WEIGHT AND C.G. SUMMARY

<table>
<thead>
<tr>
<th></th>
<th>WT</th>
<th>BA</th>
<th>% MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOFIA PRE-MOD OEW</td>
<td>266,035</td>
<td>1338.8</td>
<td></td>
</tr>
<tr>
<td>PAYLOAD</td>
<td>61,785</td>
<td>1042.0</td>
<td></td>
</tr>
<tr>
<td>BALLAST</td>
<td>10,020</td>
<td>2060.0</td>
<td></td>
</tr>
<tr>
<td>PROJECTED SOFIA ZFW</td>
<td>337,840</td>
<td>1305.9</td>
<td>14.6</td>
</tr>
<tr>
<td>FUEL</td>
<td>347,985</td>
<td>1279.3</td>
<td></td>
</tr>
<tr>
<td>TAXI GROSS WEIGHT</td>
<td>685,825</td>
<td>1292.4</td>
<td>10.5</td>
</tr>
</tbody>
</table>
Instrument Flight Rules (IFR) Operation

IATM 2000 feet/minute climb capability - standard course at most efficient speed (mach 0.84), achieving 300 feet/minute climb capability with door closed/flight reference at cruise altitude after all engine start up procedures. Elevation climb capability for two cases of higher winds. Elevation climb capability for the SOFIA science mission: The actual parameters' time or above 41,000 feet is plotted against the standard 'E' with existing engines/Performance capability for

The chart shows the standard 'E' being 747SP
AIRCRAFT PERFORMANCE FOR SCIENCE MISSION

NOTES:
1. OEW = 265,259 LBS
2. CLIMB WITH DOOR CLOSED
3. ALTITUDE = 300 FT/Min ROC
4. CRUISE AT .84 MACH
5. LOITER AT BEST ENDURANCE MACH
6. 5% FUEL FLOW CONSERVATISM
7. FUEL RESERVE: 5% INITIAL FUEL + 30 MIN SL HOLD

DRAG = 0 SQ. FT.  
RAMP WEIGHT = 540,000 LBS

DRAG = 20 SQ. FT.  
RAMP WEIGHT = 485,000 LBS
associated increase in water vapor overburden would decrease operational sensitivity.

The performance of the telescope is affected by the changes in atmospheric conditions, and the overall system design needs to be optimized to ensure the best performance. The telescope's performance is also affected by the changing weather conditions, and the system design needs to be robust to handle these changes. The results from the baseline analysis showed that the telescope's performance was not significantly affected by the changes in weather conditions.
## REQUIREMENTS SENSITIVITY

<table>
<thead>
<tr>
<th>Baseline</th>
<th>Change</th>
<th>Design Cost</th>
<th>Build Cost</th>
<th>Aircraft Performance</th>
<th>Mission Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Telescope Size</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0 Meter F-1</td>
<td>-10%</td>
<td>No Change</td>
<td>Decreased (Slight)</td>
<td>Increased (Slight)</td>
<td>Decreased</td>
</tr>
<tr>
<td><strong>Payload Weight</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>62,465 lbs</td>
<td>-10%</td>
<td>No Change</td>
<td>Decreased (Slight)</td>
<td>Increased (Slight)</td>
<td>No Change</td>
</tr>
<tr>
<td><strong>Aperture Size</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FOV 20° - 60°±12° 3.0 Meter</td>
<td>-10%</td>
<td>No Change</td>
<td>Decreased (Slight)</td>
<td>Increased (Slight)</td>
<td>Decreased</td>
</tr>
<tr>
<td><strong>Aero-Optics Interface</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fence and Alt Ramp</td>
<td>Alt Ramp</td>
<td>Decreased</td>
<td>Decreased</td>
<td>Increased</td>
<td>???</td>
</tr>
<tr>
<td><strong>Scientific Mission</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Altitude - 41000 ft. Time on Station 7 hours</td>
<td>± 10%</td>
<td>No Change</td>
<td>No Change</td>
<td>± 600 Ft. Change in Initial Altitude</td>
<td>No Change</td>
</tr>
</tbody>
</table>
Hydraulic mobility to the pallets. Second, the motors must operate off aircraft 400 Hz power. Another might be to add pallets. Naturally any system that is chosen will require modifications to meet SOFIA's unique needs. For one, operations is expected to weigh approximately 15,000 lbs. The ground-based cooling equipment that is off loaded at each base of circulating fan and refrigerant coil will add approximately 400 lbs, while having those along with the considerable amount of weight forward. It is critical to minimize support equipment weight there. A weight must also be restricted, as it is a critical factor for SOFIA. Since the telescope already adds a pressure (27 psi).

The airborne environmental control equipment also has a set of constraints that must be adhered to. Constraints never occur within the cavity. There are two objectives for the cavity's environmental control. The first is the ability to cool the coupled.

Cavity Environmental Control
CAVITY ENVIRONMENT CONTROL OBJECTIVES AND CONSTRAINTS

OBJECTIVES:

• COOL CAVITY AND TELESCOPE TO -30°F, WITH A ONE HOUR TIME CONSTANT
• CONDENSATION SHALL NEVER OCCUR WITHIN THE CAVITY

CONSTRAINTS:

• DIMENSIONAL SIZE
• 400 Hz POWER
• LOW TEMPERATURE OPERATION
• LOW PRESSURE OPERATION
• MOBILITY
• FLEXIBILITY
• SELF-CONTAINED
• WEIGHT
The cooling medium for the cavity is oil. The oil can be cooled on or off-board the aircraft. There are advantages and disadvantages associated with off-board cooling.

Alternatively, yields an extra logistic headdache (if the liquid nitrogen is needed elsewhere).

Therefore, the oil-based cooling alternative was chosen.

The equipment is composed of approximately one hour can be achieved. All the cooled condenser Yokohama.

Cooling Approach Options
COOLING APPROACH OPTIONS

COOL

STORED CAPACITY

MECHANICAL COOLING

CHILLED

ONBOARD

OFF BOARD

REFRIGERATION
For further details, addition to those items an immersion heater is required to heat up the coil. See sequence of operation. In addition to those items an immersion heater is required to heat up the coil. See sequence of operation. In addition to those items an immersion heater is required to heat up the coil. See sequence of operation. In addition to those items an immersion heater is required to heat up the coil. See sequence of operation. In addition to those items an immersion heater is required to heat up the coil. See sequence of operation.

This method would be difficult to control. It only consumes 40 minutes and 90 gallons of liquid nitrogen. This method would be difficult to control. It only consumes 40 minutes and 90 gallons of liquid nitrogen. This method would be difficult to control. It only consumes 40 minutes and 90 gallons of liquid nitrogen. This method would be difficult to control. It only consumes 40 minutes and 90 gallons of liquid nitrogen. This method would be difficult to control. It only consumes 40 minutes and 90 gallons of liquid nitrogen.

The equipment is designed to be a supply of condensate moisture. Two use dehumidification and two use pumping. The equipment is designed to be a supply of condensate moisture. Two use dehumidification and two use pumping. The equipment is designed to be a supply of condensate moisture. Two use dehumidification and two use pumping. The equipment is designed to be a supply of condensate moisture. Two use dehumidification and two use pumping.
MOISTURE CONTROL APPROACH OPTIONS

- REMOVE MOISTURE
  - PURGE
  - SEAL
  - SLOW FLOW
  - PRESS.
  - DILUTE
  - REFRIGERATION
  - DEHUMIDIFY
  - DESICCANT
any output modifications and if provides simpler capacity control.

Two possible methods of achieving the heating requirement are: (1) bleed hot compressed air from the
neccessary to obtain a 3 hour warm up.

water) and heater (2) 15 kW (could provide this capacity). A heating rate of 100,000 BTU/HR is
moisture will not condense onto the equipment. An on-board fan (able to supply 4,000 cfm at 1" of
the ground ambient temperature. Thus, when the cavity is opened up on the ground, intelligently
The cavity and its contents require heating upon descent. The equipment must be heated up to at least
Reheated uprights.
REHEAT APPROACH OPTIONS

- ENGINE EXHAUST
- ELECTRICAL
Preparation for Acceptance

Sequence of Operations

Preparation for Acceptance

Sequence of Operations
SOFIA CAVITY COOLING SYSTEM
SEQUENCE OF OPERATIONS

PREPARATION FOR ASCENT

1. BEGIN POSITIVE PRESSURIZATION OF CAVITY BY TURNING ON LIQUID NITROGEN SYSTEM

2. START REFRIGERATION/DEHUMIDIFICATION
   
   a) CONDENSE MOISTURE OUT JUST ABOVE FREEZING. DRAIN OFF MOISTURE.
   
   b) CONTINUE REFRIGERATION/DEHUMIDIFICATION DOWN TO -40°F
   
   c) DEFROST THE -40°F COIL WHEN THE PRESSURE DROP ACROSS THE COIL BECOMES TOO HIGH

3. AFTER DEHUMIDIFICATION IS COMPLETE, BEGIN COOLING THE CAVITY USING THE SAME REFRIGERATION SYSTEM AS ABOVE. COOL CAVITY TO -30°F.
conditions are re-established after landing. The door remains closed until request is completed.

flow is established, turn the heater coils off. The system heats the cavity until ground ambient
that in the last paragraph of "preparation for ascent". Next, start the onboard circulation fan. Once
After door closure, resume positive pressurization of the cavity. Again, the operation is the same as
Descent

opening the cavity door.

The cavity maintains a positive pressure between inside and the outside. The operation is the same as
Ascent

Sequence of Operations (contd)
SOFIA CAVITY COOLING SYSTEM
SEQUENCE OF OPERATIONS

ASCENT

1. MAINTAIN PRESSURIZATION OF CAVITY USING LIQUID NITROGEN SYSTEM. DISCONTINUE AT ALTITUDE.

DESCENT

1. RESUME POSITIVE PRESSURIZATION OF CAVITY USING LIQUID NITROGEN SYSTEM.

2. HEAT THE CAVITY WITH THE ELECTRIC COILS. CONTINUE TO HEAT EQUIPMENT TO AMBIENT GROUND TEMPERATURE.

3. DISCONTINUE PRESSURIZATION AND HEATING WHEN THE CAVITY EQUIPMENT IS AT OR ABOVE AMBIENT TEMPERATURE.
completed. The power requirements for the various components are shown. The ground cooling and purging system

expected to need approximately 38 kilowatts. This operation occurs after the science observing is
envisioned will require a maximum of 61 kilowatts for operation. The onboard heater and fan is
# POWER REQUIREMENTS

## CHILLER:

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>QUANTITY</th>
<th>POWER (EA)</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>kW</td>
<td>kW</td>
</tr>
<tr>
<td>HIGHSTAGE COMPRESSOR</td>
<td>1</td>
<td>26.1 (35)</td>
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<tr>
<td>LOWSTAGE COMPRESSOR</td>
<td>1</td>
<td>11.2 (15)</td>
<td>11.2</td>
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<tr>
<td>CONDENSER FANS</td>
<td>3</td>
<td>2.2 (3)</td>
<td>6.6</td>
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<tr>
<td>SYSTEM PUMP</td>
<td>1</td>
<td>5.6 (7-1/2)</td>
<td>5.6</td>
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<tr>
<td>BYPASS PUMP</td>
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<td>2.2</td>
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## FAN COIL (EXTERNAL):

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<tbody>
<tr>
<td></td>
<td></td>
<td>kW</td>
<td>kW</td>
</tr>
<tr>
<td>MIXING PUMP</td>
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<tr>
<td>IMMERSION HEATER</td>
<td>1</td>
<td>10.0</td>
<td>10.0</td>
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<tr>
<td>FAN</td>
<td>1</td>
<td>3.7 (5)</td>
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## FAN AND REHEAT (ON BOARD):

<table>
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<th>POWER (EA)</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>kW</td>
<td>kW</td>
</tr>
<tr>
<td>FAN</td>
<td>1</td>
<td>2.2 (3)</td>
<td>2.2</td>
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<tr>
<td>ELECTRIC REHEAT</td>
<td>2</td>
<td>18.0</td>
<td>36.0</td>
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## MISCELLANEOUS:

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<th>TOTAL</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>kW</td>
<td>kW</td>
</tr>
<tr>
<td>CONTROL POWER</td>
<td>-</td>
<td>.5</td>
<td>.5</td>
</tr>
<tr>
<td>HYDRAULIC PUMPS</td>
<td>2</td>
<td>5.6 (7-1/2)</td>
<td>11.2</td>
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</tbody>
</table>

TOTAL 109.7 kW

* SIMULTANEOUS OPERATION, MAXIMUM POWER DRAW 61 kW

** ON BOARD REQUIREMENTS DURING FLIGHT, 38.2 kW
Demineralization by desalination should not be ruled out yet. Some of its drawbacks may not be too difficult to overcome.

Demineralization by desalination would require extension from both a power and demineralization standpoint. If especially reductions are made, however, cool down time would reduce extension.

The cooling equipment's power draw border on the high side. Reducing equipment size would be useful to complete mission.

However, the compressors would be required to operate during the entire mission compared to that of the bearing. However, the compressors would be required to operate during the startup cycle's make-up air requirements. This additional compressed air requirement is small for the purge cycle's make-up air requirements. Additional compressed air requirement is small for the purge cycle's make-up air requirements. Additional compressed air could be used if the cavity's leak rate is maintained at the level predicted hereinafter in the air, which is 40 SCFM. More detail is required to define the compressor system. Currently a system similar to those larger offshore may be accomplished using modified, but not the most part, oil-free shell equipment and technology.

Concerns: Environmental control within the cavity is feasible from both a financial and technical standpoint. It is feasible and concerns.
FEASIBILITY AND CONCERNS

FEASIBILITY

- TECHNICAL FEASIBILITY ESTABLISHED
- USE OF SLIGHTLY MODIFIED/EXISTING EQUIPMENT ENVISIONED

CONCERNS

- COMPRESSOR SYSTEM REQUIRES FURTHER DEFINITION
- COOLING EQUIPMENT POWER NEEDS ARE GREAT
- DESICCANT OPTION SHOULD NOT BE RULED OUT
Conclusions
CONCLUSIONS

- TECHNICAL AND COST FEASIBILITY ESTABLISHED, USING MODIFIED AND "OFF THE SHELF" EQUIPMENT

- GROUND COOLING/DEHUMIDIFICATION EQUIPMENT PALLETIZED FOR EASE OF GROUND/AIR TRANSPORT

- REHEAT SYSTEM CARRIED ON-BOARD, WITH MINOR WEIGHT AND VOLUME PENALTIES, AND LOW COMPLEXITY
The chart summarizes the major interfaces between the aircraft system and the other SOPFA...
AIRCRAFT INTERFACES SUMMARY

- STRUCTURAL/MECHANICAL
  - TELESCOPE/BULKHEAD MOUNT
  - BULKHEAD FEEDTHROUGHS
  - BULKHEAD TO TELESCOPE CABLE/LINE ROUTING AND ATTACHMENT
  - CABIN EQUIPMENT MOUNTING (CONSOLES, RACKS, ETC.)
  - CABIN CABLE/LINE ROUTING
  - GROUND COOLING EQUIPMENT/AIRCRAFT ATTACHMENT
- THERMAL
  - CAVITY INSULATION
  - CAVITY PRECOOL WITH AIRCRAFT AIR CONDITIONING EQUIPMENT (OPTIONAL)
  - CABIN EQUIPMENT COOLING (IF NECESSARY)
- ACOUSTIC
  - CAVITY/CABIN ISOLATION
  - CABIN SOUND BARRIER
- ELECTRICAL POWER
  - POWER DISTRIBUTION
- COMMUNICATIONS
  - "AIR DATA"/INS TO CENTRAL PROCESSOR
  - POINTING CONTROL TO AUTOPILOT
The design drivers analyzed during the study were selected on the basis of significant cost and ramp and flight-type design. It is a major performance/cost driver and should be studied further.

The payload required to satisfy current and future requirements are 1.420 lbs for a total payload of 71.85 lbs. (Baseline). The payload weight of approximately 44,000 lbs. is approximately 5.5 hours for a ramp weight of approximately 46,000 lbs. (Baseline).

For the concept developed, the potential benefits are greater than 45,500 lbs. (Baseline). The potential performance improvement in terms of equivalency to the baseline configuration, based on the performance in terms of equivalency that plate area for the baseline configuration, was performed that estimated the potential performance impact in flutter modes.

The study has confirmed the reliability of installing a 3-meter class telescope in a well. The Boeing 747SP remains the platform of choice for the SOFIA mission. Of the several conclusions reached during the BMD phase a study, the following appear to be most significant:

1. The concept was confirmed the reliability of installing a 3-meter class telescope in a well. The Boeing 747SP remains the platform of choice for the SOFIA mission. Of the several conclusions reached during the BMD phase a study, the following appear to be most significant:

Conclusions and Major Issues
CONCLUSIONS

• BOEING 747SP REMAINS AIRCRAFT OF CHOICE

• INSTALLATION CONCEPT APPEARS FEASIBLE

• DRAG ANALYZED AND AIRCRAFT PERFORMANCE ESTIMATED

• PAYLOAD/BALLAST RELATIONSHIP DEVELOPED

• MAIN DESIGN DRIVER IS POROUS FENCE - COST AND PERFORMANCE
enhanced or even upgraded ultimate to achieve required mission performance.

In an ultimate decision, after the system weight and drag values become settled, on the need for
provisions, there may likely needs to be accomplished to identify conflicts and their resolution and,
detailed analysis of changes required for SOPA implementations. (E.1) Structural changes, power
development control system where a significant evaluation effort is needed for control system
environmental control system, where sequel to appear strong/highly diverse and further assessment,
Efforts are needed as a result of the currency location, should be examined in further detail,
Routing of all cables as a result of the currency location, should be examined in further detail,
Routing of all cables may have cost and performance impacts. These includes: control cables, were
The final category, aircraft system revisions, includes those systems concepts whose potential revision

The second category, configuration concerns, addresses structural/dynamical issues which require

critical inputs to a preliminary CFD.

The second category, configuration concerns, addresses structural/dynamical issues which require

Critical inputs to a preliminary CFD.

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Critical inputs to a preliminary CFD.
ISSUES AND RECOMMENDATIONS

- PROGRAMMATIC
  - TELESCOPE SIZE
  - CAVITY ENVIRONMENTAL CONTROL
  - AERO-OPTICS INTERFACE
  - INTERFACE CONTROL DOCUMENT
- CONFIGURATION CONCEPT
  - STRUCTURAL/DYNAMIC UNCERTAINTIES
  - DETAILED CONCEPT DEVELOPMENTS
  - BULKHEAD WEIGHT VS DEFLECTION REQUIREMENTS
- AIRCRAFT SYSTEMS REVISIONS
  - CONTROL CABLES
  - ENVIRONMENTAL CONTROL SYSTEMS
  - ELECTRICAL/AVIONIC SYSTEMS
  - ENHANCED/UPGRADED POWER PLANTS
SECTION 6
INTEGRATION AND TEST

6.1 Scope
6.2 Integration Program Description
6.3 Test Program Description
6.4 Summary and Conclusions
elements at the observatory level, they are built up into subsystems, and then into functional interface tests between subsystems and major

elements. In general, it is necessary to perform both environmental and functional tests on hardware elements as

until... For each program element, and this will have to be addressed in future phases. However, in

which they are performed. It is too early in the SOPFA program to define what is meant by component,

when the test program must address not only the types of testing required, but the hardware "levels" at

also.

To start of the experimental flight series, to the facility simulator shall be provided early enough to assure successful integration prior

access to the facility simulator shall be provided early enough to assure successful integration with the facility.

hardware/software at ARC to enable integration and checkout of the experimental with the facility.

will provide the necessary interface documentation to the flight test team to implement and test their experimental at their own facility. The SOPFA

be routinely installed and removed from the SOPFA facility during its lifetime. Thus, it is incumbent on

require observation program is quite different from a space program, in that many experimental will

The major elements involved in the SOPFA AC program are shown. It is envisioned that each element,

Victor program elements and to provide a basis for cost estimate.

define the scope, level, and general tasks required. In order to assign responsibilities among the
trochical reliability is not an issue for the SOPFA AC program. It is important in this early phase to

testing. The lower component level through build-up stress to the system (observatory) level. Although

program is the planning, notification, and recovery of system integration and testing (IT). Flowing

appropriate effort required for the successful accomplishment of any complex hardware development

Integration and Test Program
SOFIA INTEGRATION AND TEST PROGRAM
SCOPE

- INTEGRATION PROGRAM - MAJOR ELEMENTS
  - TELESCOPE ASSEMBLY
  - CONSOLES AND ELECTRONICS SUBSYSTEM
  - AIRCRAFT SYSTEM
  - GROUND SUPPORT SYSTEM

- TEST PROGRAM
  - LEVELS
    - COMPONENT
    - UNIT
    - ASSEMBLY
    - SUBSYSTEM
    - SYSTEM (OBSERVATORY)

- TASKS
  - ENVIRONMENTAL
  - ACCEPTANCE
  - QUALIFICATION
  - FUNCTIONAL
preparation

integration program description
SOFIA INTEGRATION PROGRAM
PREPARATION

• DOCUMENTATION
  - SUBSYSTEM SPECIFICATIONS
  - DRAWINGS: SYSTEM DESIGN/FABRICATION/INSTALLATION
  - DESIGN REPORTS/SYSTEM DESCRIPTIONS/TECHNICAL ANALYSES
  - INTERFACE CONTROL DRAWINGS/DOCUMENTS
  - TEST PLANS AND PROCEDURES
  - OPERATION MANUALS

• ASSOCIATED TASKS
  - CONFIGURATION CONTROL
  - SAFETY, RELIABILITY, AND QUALITY ASSURANCE
  - TECHNICAL REVIEWS
  - SCHEDULE PLANNING AND MAINTENANCE
  - SPARES PROGRAM
Final integration of the telescope assembly.

Integration to the next level. Further functional testing would take place at the second level(s), before subsequent necessary testing would take place at the unit level shown on the left hand side, before subsequent subsystems and sub-assemblies. It is envisioned that initial functional/environmental testing (as

The chart depicts a preliminary concept for the build-up of the telescope assembly from its units.
Observatory Level Integration and Test
INTEGRATION AND TEST FLOW DIAGRAM
TO OBSERVATORY LEVEL

CONSOLES
SYS ELECTRONICS AND CONTROLS
COMPUTER AND S/W
WIRING AND CABLING
COMMAND GEN AND DATA SUBSYS

TELESCOPE ASSEMBLY

CONSOLES AND ELECTRONICS SUBSYSTEM

INTEGRATED TELESCOPE SYSTEM

MODIFIED AIRCRAFT SYSTEM

AIRCRAFT
A/C REFURBISHMENT
CAVITY CONSTRUCTION
BOUNDARY LAYER FENCE
APERTURE DOOR AND SHIELD
A/C ELECTRICAL MODS
CAV ENVIR CNTRL SYS

GROUND SUPPORT SYSTEM

UNIT INSTALLATION
INTEGRATED SYS WIRING

AIRBORNE OBSERVATORY
The test program for the SOFIA major elements will be performed in various phases. For the aircraft modification element, early (Phase B) wind tunnel testing is planned using a sub-scale mockup of the aircraft forward fuselage section with the cavity modification. These tests will identify an acceptable approach which creates minimum drag. The tests will also characterize the dynamic and acoustic loads in the cavity and wind loads on the telescope structures. Measurements will also be taken of overall forces/torques on the fuselage to assess stability and control margins. After the aircraft modification is complete, flight testing will be performed to verify aircraft performance, stability, and control, and the cavity environments; it has not been determined as yet whether these flight tests will use Telescope System mass simulators or will await actual installation of the Telescope System.

The integrated Telescope System elements will undergo functional and environmental testing at various levels during the build-up as previously discussed. Environmental testing will be performed in a ground facility, or after aircraft installation, verification of the pointing control system will, of course, require testing during flight.

As previously noted, the functional/environmental testing of the experiments (science instrument and control electronics) is the responsibility of the investigator team at their home facility. Upon delivery of the experiment equipment to NASA-Ames prior to a flight series, the experiment will undergo interface compatibility and functional tests using an ARC-based Telescope System simulator. The latter will duplicate all Telescope System interfaces and functions, allowing complete checkout of the experiment prior to installation in the aircraft.
ENVIRONMENTAL ACCEPTANCE TESTS

- TESTS
  - VIBRATION
  - SHOCK
  - ACOUSTICS
  - THERMAL
  - LOW PRESSURE
  - HUMIDITY
  - ELECTRICAL POWER
  - EMI/EMC
- ENVIRONMENT LEVELS
  - ACCEPTANCE: 1.25 TIMES EXPECTED ENVIRONMENTS - AS APPLICABLE
  - QUALIFICATION (SELECTED COMPONENTS): 1.5 TIMES
The SOFIA program test approach will be analogous to a "protoflight" approach used in space hardware programs, that is, testing will be performed on the actual flight hardware, avoiding the expense of a prototype development program. This includes Telescope System and aircraft modification hardware, at appropriate build-up levels. For acceptance testing, the dynamic test environment and aircraft (shown in the chart) will be at levels that are 1.25 times the predicted operating ranges. It is possible that selected items, such as power supply voltages, greater or less than the expected operating range, will be subjected to qualification-level tests, these tests will verify a 1.5 design margin for dynamic loads. Finally, spares and refurbished units will be screened for workmanship by testing to acceptance amplitudes and duration.
MAJOR SYSTEM FUNCTIONAL AND ENVIRONMENTAL TESTING

- AIRCRAFT SYSTEM
  - WIND TUNNEL TESTS OF CAVITY MODIFICATION
  - SHEAR LAYER CONTROL CONCEPTS
  - ACOUSTIC AND WIND LOADS IN CAVITY WITH TELESCOPE MODEL
  - DRAG INCREMENT, STABILITY, AND CONTROL
  - FLIGHT TESTS (OBSERVATORY LEVEL) - VERIFICATION
    - AIRCRAFT PERFORMANCE
    - STABILITY AND CONTROL
    - CAVITY ENVIRONMENT/SHEAR LAYER/DYNAMIC LOADS

- TELESCOPE SYSTEM
  - COMPONENT/ASSEMBLY LEVEL FUNCTIONAL AND ENVIRONMENTAL
  - INTEGRATED SYSTEM FUNCTIONAL AND ENVIRONMENTAL

- SCIENCE INSTRUMENTS
  - FUNCTIONAL/ENVIRONMENTAL TESTS AT INVESTIGATOR FACILITY
  - TELESCOPE INTERFACE TESTING USING ARC TELESCOPE SYSTEM SIMULATOR(S)
Summary and Conclusions
INTEGRATION AND TESTING PROGRAM NEEDS

- WELL-DEFINED STATEMENTS OF WORK FOR ALL ELEMENTS
- INTERFACE DEFINITION AND REQUIREMENTS
- PERFORMANCE RESPONSIBILITIES
- TESTING RESPONSIBILITIES
- CORRECTIVE ACTION RESPONSIBILITIES
SECTION 7
GROUND SUPPORT SYSTEM

7.1 Ground Support Facilities

7.2 Aircraft Ground Support Equipment
The proposed location, between ARC Flight Line buildings N245 and N249, is accessible from existing roads and is arranged to include a building and hangar facility. The proposed lease of this location for SOFIA thus fits in with the Center's Master Plan for land use.

The proposed lease will provide: a controlled and covered environment in which telescope equipment may be housed; crane and vehicle space for telescope and equipment repair and removal; and office and storage and office space for telescope and equipment support services. The proposed lease will accommodate a 24-hour operation.

KAO). This project provides all elements for project development, including automated precision alignment, 750-Arcsec pointing, reconditioning of the Stratospheric Observatory for Infrared Astronomy (SOFIA), and establishment of a 2-meter telescope to conduct science.

Scope

Ground Support Facilities

7.1
GROUND SUPPORT FACILITIES
SCOPE

• 16,600 SQUARE FOOT, TWO STOREY OFFICE/LABORATORY BUILDING
  - OFFICE, LIBRARY, CONFERENCE ROOM AREAS
  - LABORATORIES: TELESCOPE AND DATA SYSTEMS SIMULATORS, STATIC TEST FACILITY
  - EXPERIMENTAL EQUIPMENT SUPPORT
  - SHOP AND STORAGE AREAS

• 6,600 SQUARE FOOT, HIGH BAY NOSE DOCK
  - CONTROLLED AND COVERED ENVIRONMENT
  - CRANE AND RIGGING EQUIPMENT
  - MIRROR COATING FACILITY
  - OFFICE AND STORAGE SPACE FOR GROUND SUPPORT PERSONNEL AND EQUIPMENT

• LOCATION: BETWEEN BUILDINGS N248 AND N259, ADJACENT TO THE AMES FLIGHT RAMP
  - CONSISTENT WITH CENTER LAND USE PLAN
  - ACCESSIBLE FROM EXISTING RAMPS AND TAXIWAYS
SOFIA Operations Schedule.

Completion in 1990 is critical for support of these tests. Facility non-completion can impact the
development of Telescope, Instrumentation, and Ground Support Facilities. Ground Support Facilities
Demands for Office, Laboratory, and Hangar Facilities is driven by the Master SOFIA Schedule, which
includes solution for remaining within the Center's plan for land use.

The proposed solution, an office/laboratory building and a 747 nose dock, is the most cost
efficient solution within the existing flight hangar (NZ111), and constructed a new full hangar with office and laboratory.

Ground Support Facilities have been identified and acceptable within the

feasibility of SOFIA.

The Boeing 747 aircraft proposed for use as the platform for SOFIA is both larger and heavier than any

Installation
GROUND SUPPORT FACILITIES
JUSTIFICATION

- EXISTING GROUND SUPPORT FACILITIES INADEQUATE FOR BOEING 747

- EXISTING OFFICE/LABORATORY FACILITIES INADEQUATE FOR SOFIA OBSERVATORY SUPPORT

- NO ACCEPTABLE ALTERNATIVES IDENTIFIED WITHIN THE CENTER

- DEMAND DRIVEN BY MASTER SOFIA SCHEDULE:
  - EQUIPMENT INSTALLATION AND CALIBRATION IN EARLY 1991
  - GROUND SUPPORT TESTS IN LATE 1991
  - FLIGHT TESTS IN LATE 1992
The accompanying list applies to Retract Maintenance and Servicing requirements. Note that the equipment listed is a short list of minimum equipment requirements. It should be noted that kits, parts, and instruments are required for routine aircraft maintenance and servicing. In addition, miscellaneous tools, engine and APU change kits, and engine stands are also necessary. The landing gear (8 jacks total), as well as a complement of maintenance stands (6 total), and a jack is required to raise the aircraft to a feasible height. A jack capable of supporting the aircraft is required. The Boeing 747SP aircraft is proposed for use as the platform for SOFIA. It is both larger and heavier than current aircraft.
<table>
<thead>
<tr>
<th>Ground Support Facilities</th>
<th>Aircraft Ground Support Equipment</th>
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<tbody>
<tr>
<td>Stair Truck</td>
<td>Generator Set</td>
</tr>
<tr>
<td>Towing Tractor/Bars</td>
<td>Hi-Ranger Truck (Cherry Picker)</td>
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<tr>
<td>Air Conditioner Unit</td>
<td>Engine Change Kit/Stand</td>
</tr>
<tr>
<td>APU Change Kit</td>
<td>Engine Stand</td>
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<tr>
<td>Aircraft Jacks (8)</td>
<td>Work Stands</td>
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<tr>
<td>Portable Scales</td>
<td>Airspeed Tester</td>
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<tr>
<td>Miscellaneous Tools, Kits</td>
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</table>
GROUND SUPPORT FACILITY
NOSE DOCK
SECTION 8
OPERATIONS SYSTEM

8.1 Goals and General Plan for SOFIA Operations
8.2 Project Management and Administration
8.3 Investigator Selection
8.4 Ground Operations
8.5 Flight Operations
8.6 Science Data Analysis
GOALS AND GENERAL PLAN FOR SOFIA OPERATIONS

SOFIA

Ames Research Center

8.1
GOALS AND GENERAL PLAN FOR SOFIA OPERATIONS (CONTD)

• YEARLY SCHEDULE
  - 40 WEEKS FOR RESEARCH FLIGHTS @ 3 FLIGHTS/WEEK
  - 12 WEEKS FOR SUPPORT ACTIVITY
    • 3 WEEKS - AIRCRAFT PERIODIC MAINTENANCE
    • 2 WEEKS - PILOT TRAINING AND PROFICIENCY
    • 4 WEEKS - MAJOR TELESCOPE MAINTENANCE AND MODIFICATIONS
    • 3 WEEKS - "MAKE-UP" DUE TO DIFFICULTY IN SCHEDULING MON/WED/FRI FLIGHT SERIES
      (HOLIDAYS, CONTINGENCIES, GROUNDINGS, ETC.)
- Engineering, Technical, and Logistics
- Data Systems
- SSCs Under SOFIA Project Office Control, E.G.

Coordination with Support Service Contractors (SSC)

E.G. Aircraft Operations Division to Direct Daily Support and Participation

Coordination with Other Ames Groups

Quarterly Meeting of Users Subgroup, Equivalent to JMOVIP for Airborne Astronomy

Annual Meeting of All Users

SOFIA Users

Headquarters Program Office(s)

OverSIGHT

OverAll Responsibility for Administration and Management of Approved Program

SOFIA Project Office - AOG

Project Management and Administration

Ames Research Center
PROJECT MANAGEMENT AND ADMINISTRATION (CONT'D)

FISCAL MANAGEMENT

- PREPARATION OF YEARLY BUDGETS FOR "POP CALLS"
- MONITORING AND CONTROL OF APPROVED BUDGET

SCHEDULING

- PREPARATION OF YEARLY FLIGHT SCHEDULE
  - UPDATE ON MONTHLY AND WEEKLY BASIS
- ELEMENTS OF YEARLY SCHEDULE
  - RESEARCH FLIGHTS
  - FACILITY ENGINEERING FLIGHTS
  - PILOT PROFICIENCY FLIGHTS
  - AIRCRAFT AND TELESCOPE MAINTENANCE PERIODS
PASSPORTS AND VISAS

CLEARNANCES FROM HOST GOVERNMENTS

INTERNATIONAL

DOMESTIC TO USA TERRITORY

TYPES OF DEPLOYMENTS

TRANSPORT FLIGHTS - RESEARCH OR FERRY

HOTEL AND TRANSPORTATION

SOFIA FACILITY SUPPORT

AIRCRAFT SERVICES

- SUPPORT FACILITIES AT DEPLOYMENT BASE:
  - GENERAL ELEMENTS
  - DEPLOYMENT PLANNING (CONT'D)

PROJECT MANAGEMENT AND ADMINISTRATION (CONT'D)
8.3 INVESTIGATOR SELECTION

- "ANNOUNCEMENT OF OPPORTUNITY" ISSUED ANNUALLY IN OCTOBER
  - "LETTER OF INTENT" DUE NOVEMBER 30
  - PROPOSAL DUE FEBRUARY 28
- PROCESSING OF PROPOSALS
  - INITIAL RECEIPT
    - AMES UNIVERSITY AFFAIRS OFFICE
    - HEADQUARTERS INTERNATIONAL AFFAIRS OFFICE
  - CATALOGUING, REDISTRIBUTION
    - SOFIA PROJECT OFFICE
- EVALUATION AND RANKING OF PROPOSALS
  - PEER REVIEW COMMITTEE MEETS IN SPRING
    - COMPOSITION - ASTRONOMERS NOT PROPOSING FOR SOFIA FLIGHTS
    - FUNCTIONS
      - REVIEW AND RANKING OF PROPOSALS
      - RECOMMENDATIONS TO HEADQUARTERS PROGRAM OFFICE
      - SCOPE OF SOFIA RESEARCH
      - ALLOTMENT OF FLIGHTS
 Coordination with PIs - SOFIA Project Office

Monitoring of Grants and Disbursements - SOFIA Project Office

Disbursement of PI Funding - SOFIA Project Office

Scheduling of Flights - SOFIA Project Office

Notification to PI - Program or Project Scientist

Implementation of Approved Program

Allocation of Funding to PI

Assignment of Flights

PI Selection

Approved by Headquarters Program Offices

INVESTIGATOR SELECTION (CONT'D)
8.4 GROUND OPERATIONS

INTERACTION WITH PI TEAMS

- DESIGNATION OF A "MISSION DIRECTOR" FOR EACH PI
  - RESPONSIBLE FOR COORDINATING ALL SUPPORT OF A PI's FLIGHT SERIES

- TYPICAL SEQUENCE OF A PI's FLIGHT SERIES
  - COORDINATION OF REQUIREMENTS FOR SUPPORT
  - ARRIVAL OF TEAM
  - INSTALLATION OF PI's INSTRUMENT(S)
  - RESEARCH FLIGHTS
  - REMOVAL OF PI's INSTRUMENT(S)

TELESCOPE SYSTEMS MAINTENANCE

- REPAIRS ASAP TO MAINTAIN FLIGHT SCHEDULE

- PREVENTIVE MAINTENANCE
  - PLANNED SCHEDULE OF "INSPECTION AND REPAIR AS NEEDED" (IRAN)
    - SHORT-TERM ITEMS (≤ 2 DAYS)
      - NON-INTERFERENCE BASIS WITH WEEKLY SCHEDULE
    - LONG-TERM ITEMS (≥ 3 DAYS)
      - SCHEDULED GROUNDING OF AIRCRAFT FOR PERIODS OF 2 WEEKS - TWO TIMES A YEAR
PROBABILITY DONE AT A MAJOR AIRCRAFT MAINTENANCE BASE

- Scheduled grounding of Aircraft
- Semi-Annual, Annual, Biennial
- Monthly, Non-Interference Basis with Flight Schedule
- Required periodic inspections
- Repairs ASAP to maintain flight schedule

AIRCRAFT MAINTENANCE

GROUND OPERATIONS (CONTD)
8.5 FLIGHT OPERATIONS

FLIGHT PLANNING

- PI INPUT TO NAVIGATORS (TARGET LIST)
  - PRELIMINARY - ≤ 1 MONTH PRIOR TO FLIGHT
  - INTERMEDIATE - BY THURSDAY OF WEEK PRECEDING FLIGHT
  - FINAL - DAY OF FLIGHT

- TAKE-OFF (T.O.) TIME POSTED BY 1200 ON DAY OF FLIGHT

PREFLIGHT ACTIVITIES - DAY OF FLIGHT

- AIRCRAFT
  - FUELING AND PREFLIGHT CHECK OF SYSTEMS - EARLY AM

- TELESCOPE
  - PREFLIGHT CHECK OF SYSTEMS - AFTERNOON
  - PRE-COOL - T.O. - 4 HRS

- PASSENGER CHECK AT 1300 STAFF MEETING
  - SAFETY PROCEDURES, OXYGEN MASK CHECKS
FLIGHT OPERATIONS (CONT'D)

Flight Timeline - In-Flight Activities

- Preflight Briefing: Mandatory for all participants

Aircraft Lifts Off Runway

Start Taxi

Door closes

Board Aircraft

T.0. - 0 M

T.0. - 15 M

T.0. - 25 M

T.0. - 45 M

T.0. - 60 M

Open door; start observations

Start camera purge

End observations; close door

Start decent

Land

T.0. + 730 M

T.0. + 7 H

T.0. + 30 M

T.0.
FLIGHT OPERATIONS (CONTD)

FLIGHT PARTICIPANTS

• FLIGHT CREW (3)
• SOFIA STAFF (3-4)
• PI TEAM (3-8)

AUTHORITY DURING FLIGHT

• MISSION MANAGER
  - DIRECTS ALL OPERATIONS FOR FULFILLMENT OF MISSION OBJECTIVES
    AND TELESCOPE PERFORMANCE
• CHIEF PILOT
  - AUTHORITY IN ALL ASPECTS OF AIRCRAFT OPERATION AND SAFETY

ROLES DURING FLIGHT

• FLIGHT CREW
  - PERFORMANCE OF AIRCRAFT
• SOFIA TELESCOPE AND SUPPORT CREW
  - OPERATION OF TELESCOPE AND SOFIA PROVIDED DATA SYSTEMS
• PI TEAM
  - RESPONSIBLE FOR PROVIDING AND OPERATING THE DETECTING INSTRUMENT AND CONTROL SYSTEM
8.6

SCIENCE DATA ANALYSIS

DATA COLLECTION DURING FLIGHT

DATA ANALYSIS

- DEFINITIVE ANALYSIS BY PI AT HOME BASE
- QUICK-LOOK ANALYSIS DURING FLIGHT

RESPONSIBILITY OF PI

METHOD OF COLLECTION

 EITHER

SOFIA DATA SYSTEM
 OR

PI-SUPPLIED DATA SYSTEM

RESPONSIBILITY OF PI